PRICE TEN SHILLINGS AND SIXPENCE

THE JOURNAL OF
The Institution of Electrical Engineers

ORIGINALLY
The Society of Telegraph Engineers
FOUNDED 1871
INCORPORATED BY ROYAL CHARTER 1921
EDITED BY W. K. BRASHER, SECRETARY
SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C.2.
Telegrams: "VOLTAMPERE, PHONE, LONDON." Telephone: TEMPLE BAR 7676.

Vol. 87 NOVEMBER, 1940 No. 527

CONTENTS

(The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.)

		PAGE
Oil-less Metalclad Switchgear for Medium-Voltage Alternating-Current Circuits up to 660 Volts, Three-Phase	H. E. Cox and L. Drucquer	461
Maintenance of Relays and Associated Equipment	J. R. Brookman, M.E.	485
A Method of Measuring and Recording the Frequency Error of Alternating-Current Power Supplies	F. O. Morrell, B.Sc., and G. R. Oman, B.Sc.	507
Electric Cables and Fire Risks: Recent Developments and Investigations	S. W. Melsom	521
Discussion on "Fire-Fighting Equipment for Electrical Installations"		535
The Limitation of Transformer Noise	B. G. Churcher, M.Sc., and A. J. King, B.Sc.Tech.	539
Ceramic Insulations for High-Frequency Work	W. G. Robinson, B.Sc.Tech.	570
Institution Notes		577
Advertisements		At end i–xiv

E. and F. N. SPON LIMITED, 57 HAYMARKET, LONDON, S.W.1.
CHEMICAL PUBLISHING COMPANY OF N.Y. INC., 148 LAFAYETTE STREET, NEW YORK.

The Institution of Electrical Engineers.

FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

PATRON: HIS MAJESTY KING GEORGE VI.

COUNCIL, 1940-1941.

President.
J. R. BEARD, M.Sc.

Past-Presidents.
SIR JAMES SWINBURNE, BART., F.R.S.
CHARLES P. SPARKS, C.B.E.
J. S. HIGHFIELD.
F. GILL, O.B.E.
A. RUSSELL, M.A., D.Sc., LL.D., F.R.S.
W. H. ECCLES, D.Sc., F.R.S.
SIR ARCHIBALD PAGE.
LIEUT.-COL. K. EDGCUMBE, T.D.
COLONEL SIR THOMAS F. PURVES, O.B.E.
CLIFFORD C. PATERSON, O.B.E., D.Sc.
J. M. DONALDSON, M.C.
PROF. E. W. MARCHANT, D.Sc.
P. V. HUNTER, C.B.E.
PROF. W. M. THORNTON, O.B.E., D.Sc., D.Eng.
J. M. KENNEDY, O.B.E.
H. T. YOUNG.
SIR GEORGE LEE, O.B.E., M.C.
A. P. M. FLEMING, C.B.E., D.Eng., M.Sc.
JOHNSTONE WRIGHT.

Vice-Presidents.
COL. A. S. ANGWIN, D.S.O., M.C.
P. DUNSHEATH, O.B.E., M.A., D.Sc.
V. Z. DE FERRANTI.
PROF. C. L. FORTESCUE, O.B.E., M.A.

Honorary Treasurer.
E. LEETE.

Ordinary Members of Council.
L. G. BRAZIER, Ph.D., B.Sc.
E. S. BYNG.
H. J. CASH.
THE RT. HON. THE VISCOUNT FALMOUTH.
D. Z. DE FERRANTI.
P. GOOD.
H. W. GRIMMITT.
PROF. WILLIS JACKSON, D.Sc., D.Phil.
PROF. W. J. JOHN, B.Sc. (Eng.).
PROF. R. O. KAPP, B.Sc.
H. C. LAMB.
A. L. LUNN.
F. LYDALL.

Ordinary Members of Council—(Continued).
E. B. MOULLIN, M.A., Sc.D.
J. S. PRINGLE, O.B.E.
F. JERVIS SMITH.
H. W. SWANN.
A. P. YOUNG, O.B.E.

Chairmen and Past-Chairmen of Local Centres.
Argentine Centre:
M. F. RYAN, C.B.E.
*W. E. TREMAIN.

China Centre:
J. HAYNES WILSON, M.C.
*C. R. WEBB.

Irish Centre:
T. A. McLAUGHLIN, B.E., M.Sc., Ph.D.
*J. W. O'NEILL.

Mersey and North Wales (Liverpool) Centre:
J. E. NELSON.
*W. HOLTTUM, M.Eng.

North-Eastern Centre:
W. A. A. BURGESS.
*H. G. A. STEDMAN.

North Midland Centre:
W. DUNDAS.
*J. W. ATKINSON, I.S.O.

North-Western Centre:
B. A. G. CHURCHER, M.Sc.
*O. HOWARTH.

Scottish Centre:
PROF. S. PARKER SMITH, D.Sc.
*W. J. COOPER.

South Midland Centre:
H. JOSEPH.
*H. FAULKNER, B.Sc.

Western Centre:
H. R. BEASANT.
*T. E. ALGER.

* Past-Chairman.

Chairmen of Sections.
C. W. MARSHALL, B.Sc. (*Meter and Instrument*).
H. J. ALLCOCK, M.Sc. (*Transmission*).
W. J. PICKEN (*Wireless*).

Secretary.
W. K. BRASHER, B.A.

Assistant Secretaries.
F. W. HEWITT, M.Sc.; A. E. RAYNER.

LOCAL CENTRES AND SUB-CENTRES.

ARGENTINE CENTRE.
Chairman.—M. F. RYAN, C.B.E.
Hon. Secretary.—R. G. PARROTT, Tucuman 117, Buenos Aires.

CHINA CENTRE.
Chairman.—J. HAYNES WILSON, M.C.
Hon. Secretary.—J. A. McKINNEY, c/o Shanghai Power Co., P.O. Box 404, Shanghai.

IRISH CENTRE.
Chairman.—T. A. McLAUGHLIN, B.E., M.Sc., Ph.D.
Hon. Secretary.—R. N. EATON, 1, Foster Place, College Green, Dublin.

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE.
Chairman.—J. E. NELSON.
Hon. Secretary.—W. PARRY, M.Eng., "Scaur," Birkenhead Road, Gt. Meols, Hoylake, Wirral, Cheshire.

NORTH-EASTERN CENTRE.
Chairman.—W. A. A. BURGESS.
Hon. Secretary.—L. MELLOR, "Burn Brae," Heworth, Gateshead, Co. Durham.

Tees-Side Sub-Centre.
Chairman.—T. S. G. SEAWARD.
Hon. Secretary.—A. K. WANSBROUGH, B.E., "Glen Lyon," Hutton Rudby, Yarm, Yorks.

NORTH MIDLAND CENTRE.
Chairman.—W. DUNDAS.
Hon. Secretary.—K. C. COOP, M.Eng., 36, Park Place, Leeds, 1.

Sheffield Sub-Centre.
Chairman.—F. C. CLARKE, B.Sc.
Hon. Secretary.—A. C. BOSTEL, 25, Stumperlowe Mansions, Fulwood, Sheffield, 10.

[Continued on page (III) of Cover.

OIL-LESS METALCLAD SWITCHGEAR FOR MEDIUM-VOLTAGE ALTERNATING-CURRENT CIRCUITS UP TO 660 VOLTS, 3-PHASE

By H. E. COX* and L. DRUCQUER,* Associate Members.

[*Paper first received* 31*st May, and in revised form* 7*th November* 1939; *read before* THE INSTITUTION 7*th March, before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 4*th March, before the* NORTH-EASTERN CENTRE 11*th March, before the* NORTH-WESTERN CENTRE 16*th April, before the* SHEFFIELD SUB-CENTRE 17*th April, and before the* EAST MIDLAND SUB-CENTRE 23*rd April*, 1940.]

SUMMARY

This paper reviews the problems relating to medium-voltage switchgear and its application. Certain conclusions are arrived at as representing solutions to these problems, and the construction and design of appropriate air circuit-breakers and switch-fuse gear is described. The a.c. air circuit-breaker does not need magnetic blow-out coils, and test data are provided showing the effectiveness of design without such coils. High-rupturing-capacity fuses are also dealt with in so far as they affect the design of switchgear equipments. Finally, the paper considers complete switchboards built up, from the apparatus described earlier, into metal-enclosed units.

INTRODUCTION

In the early days of electricity, direct current controlled by air-break switchgear was supreme and the low voltage obtainable set a very definite limit on the amounts of power which could be concentrated into any one place. The introduction of alternating current entirely changed this state of affairs and a period of rapid progress was entered upon, characterized by ever-increasing voltage and power concentration.

Until recently the only practical way of breaking extra-high-voltage circuits was by quenching the resulting arc with oil, and oil circuit-breakers were brought to a high pitch of perfection.

The increase in size of high-voltage networks was responsible for a similar but less-marked concentration of power in the medium-voltage networks and, since the major high-voltage problem had been successfully solved by the introduction of the oil circuit-breaker, it followed naturally that a solution on similar lines could be found for the control of medium-voltage networks. The success which attended this application of the oil circuit-breaker resulted in the air circuit-breaker being relegated to the control of a.c. medium-voltage circuits of secondary importance only, and its continued development was largely influenced by the requirements of d.c. circuit control, which remained its primary field of use.

With the present practical upper limit of modern circuit-breaker rating set at 2 500 MVA at voltages up to 280 kV, it is natural to look with indifference on the design of apparatus having an MVA rating of only 1/100th, operating at a voltage of approximately 1/700th, such as is represented by a 25-MVA 400-volt breaker. This indifference is helped by the relatively less spectacular results of failure, and the limited loss of service, consequential damage, and injury to personnel. It is a little surprising, therefore, to realize that the short-circuit current which has to be dealt with in the case of the 400-volt breaker is approximately 35 000 r.m.s. amperes, as compared with approximately 5 000 for the 280-kV breaker, i.e. the smaller piece of apparatus has to deal with 7 times the fault current, which is capable of producing ~~50~~ times the mechanical stresses.

In considering any solution of this problem it is necessary to have a general picture of the complete electrical requirements which have to be met by this class of switchgear. Such a picture is briefly indicated below.

GENERAL REQUIREMENTS

Voltage Rating

The voltage range is confined to an upper limit of 660 volts (a.c.). The use of direct current is rapidly decreasing except for traction and special process work, which has demanded special study. The results achieved in this direction are outside the scope of this paper.

Load-current Rating

The requirements are extremely varied and range from 5 amperes up to and including 4 000 amperes.

Short-circuit Rating

Testing has shown that the performance of medium-voltage breakers at breaking currents in the neighbourhood of the rated breaking capacity varies very little as the voltage is altered between the limits of 220 and 660 volts. This follows logically, first from the fact that the arc on the first phase to clear can be made to extinguish at the first available current-zero, even at 660 volts; and secondly from the fact that the arc energy depends upon current and time only and not upon the circuit voltage.

Such apparatus therefore tends to have a constant breaking-capacity current-rating at various voltages, and not a constant breaking-capacity MVA rating. It is therefore logical to define the breaking-capacity rating of such equipment in r.m.s. amperes, a figure which remains constant with variations in service voltage between the limits of 220 and 660 volts.

Much discussion has centred round the upper limit of short-circuit current encountered in medium-voltage networks, but, in the authors' experience, it can be regarded as approximately 44 000 symmetrical r.m.s. amperes, which is equivalent to 50 MVA at 660 volts.

Although fault values larger than this are possible they are confined to areas immediately adjacent to sources of supply, as even a few yards of busbar or cable appreciably reduce the fault value. Apart from excep-

* British Thomson-Houston Co., Ltd.

tional cases, therefore, it is more economical to limit the short-circuit to the value stated above by suitable sub-division of the sources of supply, than to install switchgear capable of dealing with the larger values. It must also be realized that, in the case of supply from transformers, sub-division allows the transformers to be placed nearer to the actual loads which they supply, and thus results in better voltage regulation and less copper on the network as a whole. The transformers may, of course, be interconnected through the network and thus give alternative feeds to the various loads without unduly raising the maximum short-circuit kVA.

Performance

In view of the exceedingly high fault current, it is essential that the circuit be cleared as rapidly as possible to reduce burning of contacts and limit the damage at the fault to a minimum. Two very important requirements of the contacts are that they shall be able to close on faults of full rupturing capacity without welding or undue burning at least twice in succession, and that they shall be able to withstand repeated closing and opening operations at currents in excess of their normal full-load rating. The arcing structures must also withstand the opening operations. The performance should be such that the breaker can be totally enclosed, preferably in an earthed metal enclosure of small dimensions.

Thermal Capacity

The ability of the gear to withstand through short-circuits up to its rating for periods up to 5 sec. is of importance where any attempt is made to provide discriminative protection.

Fire Hazard

An analysis of electrical failures in this country indicates that few major shutdowns of electrical supply can be directly attributed to failures of oil circuit-breakers. The presence of an inflammable dielectric such as oil in electrical apparatus remains, however, as a potential fire hazard, which, although not initially responsible, may ultimately considerably extend the area of damage. It is desirable, therefore, to reduce to a minimum the possibility of electrical failure resulting in a fire.

EXISTING TYPES OF GEAR

A brief account will now be given of apparatus already developed which, it is believed, meets the above requirements.

Oil Circuit-breakers

Modern oil circuit-breakers can be and have been successfully constructed to meet the majority of specified requirements, but can be criticized in respect of: (*a*) Relatively severe contact-burning with frequent switching at currents of the order of normal up to 10 times full load. (*b*) Relatively long total-break time. (*c*) Fire hazard.

Oil has a definite sphere of usefulness in circuit interruption, particularly for the higher voltages, a field in which it appears to possess advantages that outweigh its single disadvantage of "inflammability." It seems unnecessary, however, to use it for the medium voltages, where the even more universally available air can be used in its free and natural state without any expense and continuous processing such as compressing.

Air Circuit-breakers

The usual type of air circuit-breaker embracing carbon-block contacts, whilst meeting a definite demand, is not, in the authors' experience, capable of being used on modern high-rupturing-capacity a.c. circuits. Whilst interruption at very high values of short-circuit may be obtained, the arc lengths are very considerable and circuit interruption would probably be accompanied by strikes to earth or between phases. The operation of the air circuit-breaker when closing on short-circuit leaves much to be desired. The nature of its construction and mounting also militates against its successful inclusion in metal-enclosed switchgear.

High-rupturing-capacity Fuses

There can be no doubt that the modern high-rupturing-capacity fuse is an extremely efficient piece of apparatus, admirably meeting certain essential requirements for load-current ratings up to 600 amp. With regard to interrupting capacity, not only does it meet the required ratings but it possesses the excellent quality of being inherently current-limiting. It will be appreciated, however, that such apparatus makes no pretence at meeting any requirement of circuit-making, and hence, as a solution to the complete problem, requires ancillary gear. The present available designs are also limited in their discriminative properties on heavy short-circuits.

The following represents an effort to attack the complete problem and describes equipment which, from tests already undertaken, appears to meet all requirements. The authors claim it to be a complete solution to the problem.

CIRCUIT-BREAKER DESIGN

It is recommended that the circuit-breakers employed should be of the air-break type.

The requirements of a.c. and d.c. operation are fundamentally different. In general, the rupture of a d.c. arc is more difficult than that of an a.c. arc, in which the alternating current becomes zero twice every cycle. On the other hand, the current-making problem with alternating current is much more difficult than with direct current, because the first loop of current can reach $2\frac{1}{2}$ times the breaking-capacity current, whereas the d.c. breaker has only to deal with a current equal to its rupturing capacity. Since the electromagnetic forces are proportional to the square of the current, they amount to 6 times as much with alternating current as with direct current, and the problems of contact-welding are correspondingly greater.

For a given current rupturing capacity, therefore, the d.c. breaker is characterized by comparatively light mechanism and contacting parts and a more or less large and elaborate arc chute, circuit interruption being entirely dependent on the rapid lengthening of the arc within the chute to such a value that the circuit conditions are incapable of maintaining it.

On the other hand, the a.c. breaker requires a robust mechanism and robust contact parts, but the blow-out structure can be relatively small and simple in form.

Analysis of Requirements

Before turning to the design of suitable breakers it is necessary to analyse in detail the requirements, which can be conveniently grouped as follows:—

Group 1.

Small current-capacity breakers, say of 5 to 60 amperes, chiefly used for direct-on-line motor starting, which are always required with some form of series tripping (usually thermal) and may be closed and opened several times per hour. Such breakers require a total life of more than 1 million operations. They must be suitable for inching duty on motors taking starting currents up to 7 times full-load current.

Group 2.

Medium current-capacity breakers, say of 60 to 400 amperes, used for starting motors in conjunction with some form of control gear where they are operated several times per day, and requiring a total life of 100 000 operations. They may also be used on distribution boards. These breakers are again required with series trips only, which may be of the thermal or the dashpot type.

Group 3.

Large current-capacity breakers, say from 400 to 4 000 amperes, which are required on large distribution boards and are tripped by relays or series trips with definite minimum time-delay in order to obtain discrimination. These only require a total life of about 10 000 operations.

Detail Points of Design

The detail design of these different groups of breakers varies quite considerably.

Group 1.

As these breakers are mostly used to control individual pieces of apparatus, an under-voltage release feature is nearly always required and facilities for remote control and interlocking are desirable. These requirements are best met by magnetically closing the breaker and using the closing coil to hold the breaker in. By energizing the closing coil from the line side of the circuit which the breaker controls, an under-voltage release feature is obtained.

Series trips with long time-lags amounting to 1 or more seconds at 7 times full load are required for direct-on-line motor starting. This requirement is best met by the use of thermal trips of the bimetal type, indirectly heated in the lower capacities. The indirectly-heated trips must be augmented by instantaneous magnetic series trips to afford protection on short-circuit, as otherwise there is danger of the heating elements acting as fuses before the bimetal trip has tripped the breaker.

These breakers are of strictly limited rupturing capacity, which can only be economically made 15 to 20 times the full-load ampere capacity. Thus a 30-ampere breaker has a rupturing capacity not exceeding 450 kVA at 440 volts. This rupturing capacity would be exceeded in a large number of locations where such a breaker is demanded, and it is therefore essential that these breakers be made suitable for use on high-rupturing-capacity circuits when protected by high-rupturing-capacity current-limiting fuses.

To meet this requirement the breakers, including any overload devices, must withstand, without damage, both the magnetic and the thermal effects of the current impulse permitted by the largest size of high-rupturing-capacity fuse with which they will be used. The contact design is determined by the requirements that they should be capable of repeatedly making and breaking motor starting currents and should be able to close on to the maximum peak current permitted by a high-rupturing-capacity fuse when closing on to a 25-MVA prospective short-circuit. In such cases the requirements of thermal rating can be relieved and reduced to some value in excess of the fuse time rating.

The contact life when making and breaking the motor starting current should not be less than 1 000 operations before renewal.

Group 2.

These breakers have many points in common with those of Group 1, but their larger size leads to slight differences in design. In view of the fact that they are larger and are used on distribution boards where they may remain closed continuously for periods ranging from ½ day to 1 week or even longer, it is desirable to fit them with a direct hand-closing handle with optional electrical closing of the mechanically latched-in type and not of the electrical hold-in type. This design requires a separate under-voltage release if such a feature is desirable. Thermal trips of the directly heated bimetal type are most suitable for these breakers, as they give time-lags which are long enough for motor-starting and other duties and yet not so long that they make it difficult to arrange for discrimination with the feeder breakers and high-rupturing-capacity fuses controlling them.

The 400-ampere breaker with a rupturing capacity of 20 times the full-load current would only be suitable for circuits with a prospective short-circuit not exceeding 6 000 kVA unless it were protected by high-rupturing-capacity fuses. This group of breakers must therefore be suitable also for use in series with high-rupturing-capacity fuses and hence can be designed for a thermal capacity which allows a reasonable margin over the time rating of the fuse.

Group 3.

These breakers differ very considerably from those of Group 1 or Group 2. Their greatest application is on main distribution boards, so that they have to work in conjunction with relays or series trips with considerable time-delays, even at the full rated short-circuit, in order to ensure discriminative tripping against other breakers nearer the ultimate consuming device. This means that they cannot be used in series with high-rupturing-capacity fuses, so that they have to be designed for the full rupturing capacity of the system at the point of application.

The closing mechanism should be such that either direct hand or electrical closing can be obtained as required.

Tripping should be by current transformers in conjunction with direct-acting trip coils and time-limit fuses or relays with a definite minimum time-delay. It may also be by means of series trips with a definite minimum time-delay or, where discrimination is not required, with instantaneous short-circuit tripping.

In order to meet these requirements, the breaker should be able to close on to, and latch against, a peak current of 2·55 times the rated rupturing-capacity current. It should be able to carry its rated short-circuit current for not less than 1 sec. and preferably for 5 sec. The contacts should not lift or "splutter" on a through short-circuit current with a first peak of 2·55 times the rated rupturing-capacity current.

Arcing Contacts

The best form of contacts to meet all the above requirements, particularly for motor starting and inching duty, is the butt (or contactor) type. Tests on contact arrangements in which the magnetic loop effect and pinch effect blow off the contacts show that serious welding and burning of the points of contact occur at as low as 15 000 (peak) amperes. Better performance can be obtained by carefully bedding the contacts, but as after the first opening operation the surfaces are all pitted and burned such bedding is of no practical value.

Considerable improvement is obtained by a modification such as that shown in Fig. 1, where the loop blow-off effect from *b* to *c* is reversed at the pivot *b* and counteracts the current pinch and blow-off effect from *b* to *a*. Such contacts, with reasonable spring pressure, can carry 20 000 amperes satisfactorily without spot welding taking place. Up to 25 000 (peak) amperes only very slight spot welding takes place, which is easily broken by the inherent wipe or shear action of the contacts on opening.

The only practicable way of improving this performance is to use such high contact pressures that considerable crushing of the metal at the contact points takes place. Increasing the thermal capacity of the contacts by increasing their size does not effect any improvement in respect of non-welding. The most economical way, therefore, to deal with peak currents of more than 25 000 amperes is to resort to multiple contacts.

The upper limit of 25 000 amperes per contact is true only of breakers which are designed to close on to a short-circuit and latch home, i.e. are fitted with delayed or relay tripping devices. For breakers fitted with instantaneous tripping devices, by virtue of the short time that they have to carry the current, it is possible to increase the rating of a single contact to a figure of 50 000 (peak) amperes.

Main Contacts

Heat runs have demonstrated that arcing contacts in accordance with Fig. 1, when designed robustly enough to deal with 25 000 (peak) amperes, have a normal continuous-load capacity of 200 amperes. The effect of this is that once the rupturing capacity, and thus the peak making capacity, of the breaker has been determined, the number of arcing contacts is fixed and, consequently, the normal continuous current-carrying capacity of the contacts is fixed and it is not necessary to add main contacts unless it is desired to have a continuous capacity greater than this figure.

Fig. 2 shows an arrangement of main contacts which is suitable for use with the type of arcing contacts described above. Such contacts, when silver-faced, will again carry 25 000 (peak) amperes per contact satisfactorily. In this case, the magnetic blow-off effect is reduced to extremely small proportions by making the bridging member as short as possible and carrying the main lead-in conductors as far away as possible. Here again, the main contacts must be sub-divided in exactly the same way as the arcing contacts because, in the case of break shots, the main contacts have to carry the peak rating of the breaker, which occurs before the tripping impulse can have released the breaker and transferred the current to the arcing contacts.

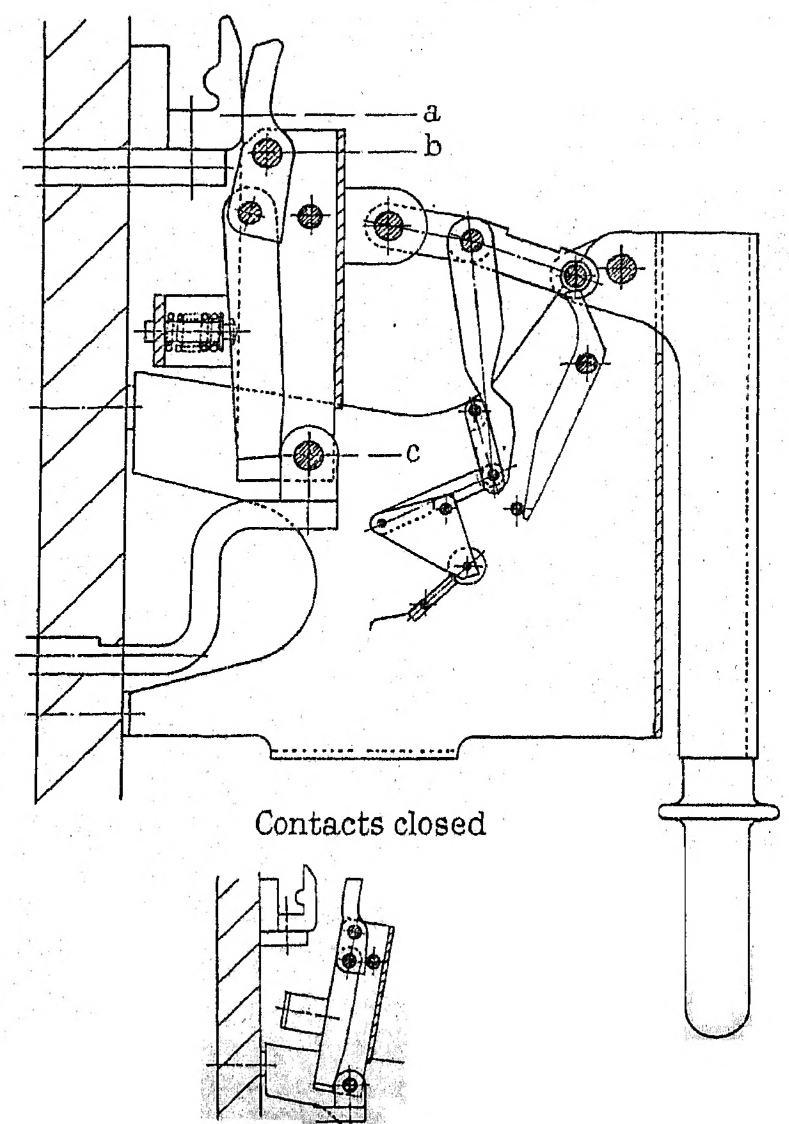


Fig. 1.—Contact arrangement for breakers without main contacts.

Mechanism

The mechanism must fulfil four requirements: First, it must be made strong enough to close the breaker against the electromagnetic forces associated with the peak current rating of the breaker and, at the same time, must overcome the very considerable shearing

forces involved in wiping the burned contacts. Secondly, in the case of it being power-operated, the mechanism must not wreck itself when closed on no-load with new contacts, the closing energy being calculated to close the breaker fully against a short-circuit with burnt contacts. Thirdly, it must be correctly buffered at the end of the opening stroke so that the acceleration due to opening

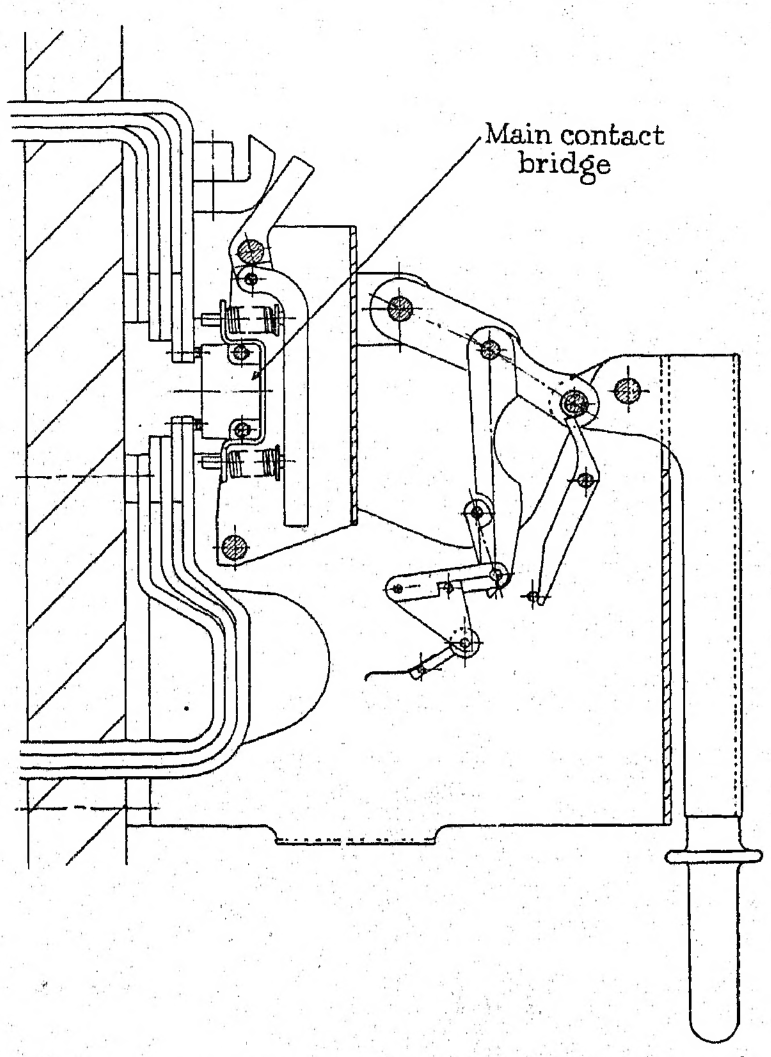


Fig. 2.—Contact arrangement for breakers with main contacts.

on short-circuit does not wreck it. Fourthly, it must be trip-free.

Arc Chutes

Experiments have shown that to ensure arc rupture the provision of an arc chute is quite unnecessary. Without any arc chutes, currents up to 37 kiloamperes were successfully broken in $2\frac{1}{2}$ cycles at 440 volts recovery voltage. The arc is so uncontrolled, however, that it causes arcs to earth and between phases unless clearances and spacings are quite prohibitive.

The requirements of a successful arc chute are as follows: First, the minimum magnetic field should be applied which is able to keep the arc continuously moving up into the chute and ensure that it is extended sufficiently to extinguish at the first or second current-zero. Any greater magnetic field than this unduly elongates the arc, developing unnecessary arc energy with the evil effects of high restriking transients due to pre-zero current-suppression. Secondly, the distance between the plates of the chute should be small enough to prevent the arc unduly lengthening itself by zig-zagging, and yet it must be large enough to ensure that the free movement of the arc is not impeded by strangulation. In effect, this means that the distance between the plates should equal the diameter of the arc at its rated rupturing capacity. Thirdly, the horns should be of such a length that the cathode spots formed at their ends are far enough apart not to cause restriking.

Figs. 3(*a*) and 3(*b*) show a horn and chute structure that meets these requirements fitted to an 800-ampere breaker with four arcing contacts in parallel. It will be noted that no magnetic blow-out coil is provided, the inherent blow-out effect of the loop formed by the arc and its leads being more than sufficient to force the arc into the chute at currents between 2 000 and 37 000 r.m.s. amperes at 440 volts recovery voltage. It was found that below 2 000 amperes the magnetic field round the arc roots was insufficient to shift them once a cathode spot had been formed, and the arc continued to burn indefinitely across AB.

Taking a section across the horn at A, the condition

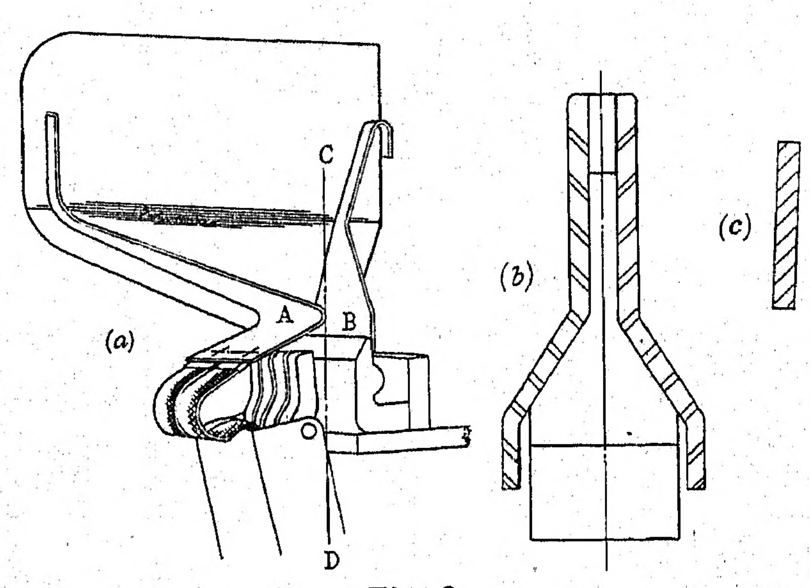


Fig. 3

(*a*) Arrangement of arcing horns.
(*b*) Front sectional elevation on CD.
(*c*) Section of arcing horn at A.

obtained is illustrated in Fig. 3(*c*). The root of the arc is then acted on by a field proportional to the current divided by the perimeter l. It is obvious that if l is made one-fifth as great, the field can be increased to approximately 5 times the strength. This can be carried out in practice by splitting the horn into five parts, as shown in Fig. 4 (see Plate 1, facing page 468). This simple modification makes the breaker quite satisfactory down to zero current. A further improvement is obtained by making the horns of steel, thus again strengthening the field at the root of the arc.

This form of chute has a relatively mild action on the arc and does not cause serious voltage-rise on breaking. Fig. 5 shows three cathode-ray oscillograms taken at approximately 27 000 arc amperes, 380 volts recovery voltage, single-phase. It will be seen that the maximum voltages do not exceed $1\cdot8$ times normal.

Phase Barriers

The effectiveness of the arc chutes is greatly increased by fitting correctly-designed phase barriers between them. The arc in the arc chute is accompanied by the release

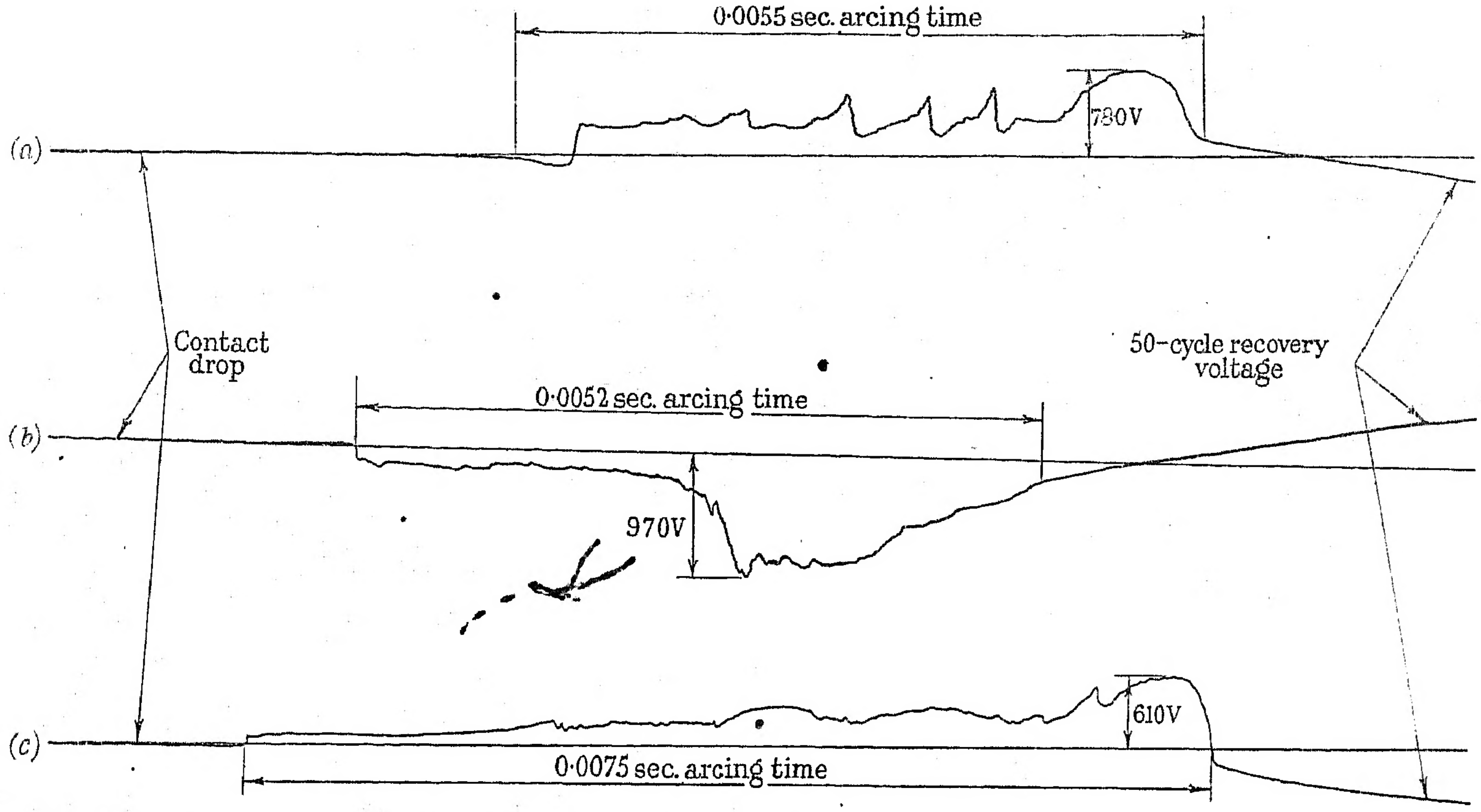


Fig. 5.—Cathode-ray oscillograms of arc voltage: single-phase tests on one phase of 400/660-volt air circuit-breaker.

(a) Current interrupted = 26 000 symmetrical r.m.s. amp. 50-cycle recovery voltage = 514 volts (peak).
(b) Current interrupted = 27 000 symmetrical r.m.s. amp. 50-cycle recovery voltage = 535 volts (peak).
(c) Current interrupted = 27 800 symmetrical r.m.s. amp. 50-cycle recovery voltage = 540 volts (peak).

of quite considerable arc energy, most of which is expended in heating up the neighbouring air to incandescence, resulting in high pressures. Some more of the energy is used up in volatilizing the contacts and arcing horns. This results in incandescent air and metal vapour being ejected from the top of the arc chute. On heavy currents, the arc itself also partially leaves the top of the chute. It is necessary to ensure that these gases are cooled and the metal vapour condensed before they are allowed to strike earthed metal or mingle with those from a neighbouring phase. This can be conveniently carried out by means of continuous U-shaped phase barriers which form an expansion chamber and direct the gases down the sides of the chutes and cool them by mingling with cold air. Fig. 6 (Plate 1) shows a suitable set of barriers applied to a 25-MVA 440-volt breaker.

Overload Trips

To give discriminative protection the tripping means must have a definite and adjustable tripping time even at the full rated short-circuit current. Provided the breaker has sufficient thermal capacity, this requirement can be met by using current transformers and some form of relay such as an induction relay with definite minimum time-delay. Such arrangements are, however, inherently expensive and usually require an auxiliary tripping supply.

The normal forms of series tripping devices using suction discs or oil dashpots are unsuitable as they become instantaneous at high overloads owing to cavitation between the disc or plunger and the oil surface. This difficulty has been overcome by an arrangement suggested to the authors in which the piston is pushed into the dashpot instead of being pulled

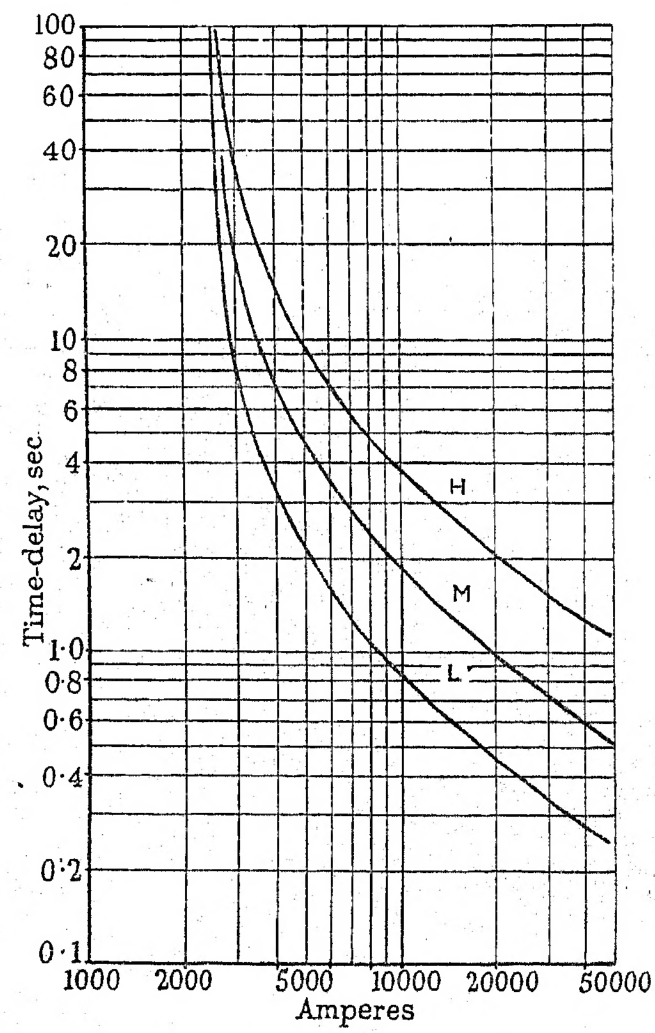


Fig. 7.—Characteristics of compression-type dashpot fitted to 1 600-amp. air circuit-breaker using medium-viscosity dashpot oil.

Curve H: high setting of dashpot.
Curve M: medium setting of dashpot.
Curve L: low setting of dashpot.
Series trip set to operate at 2 400 amp.

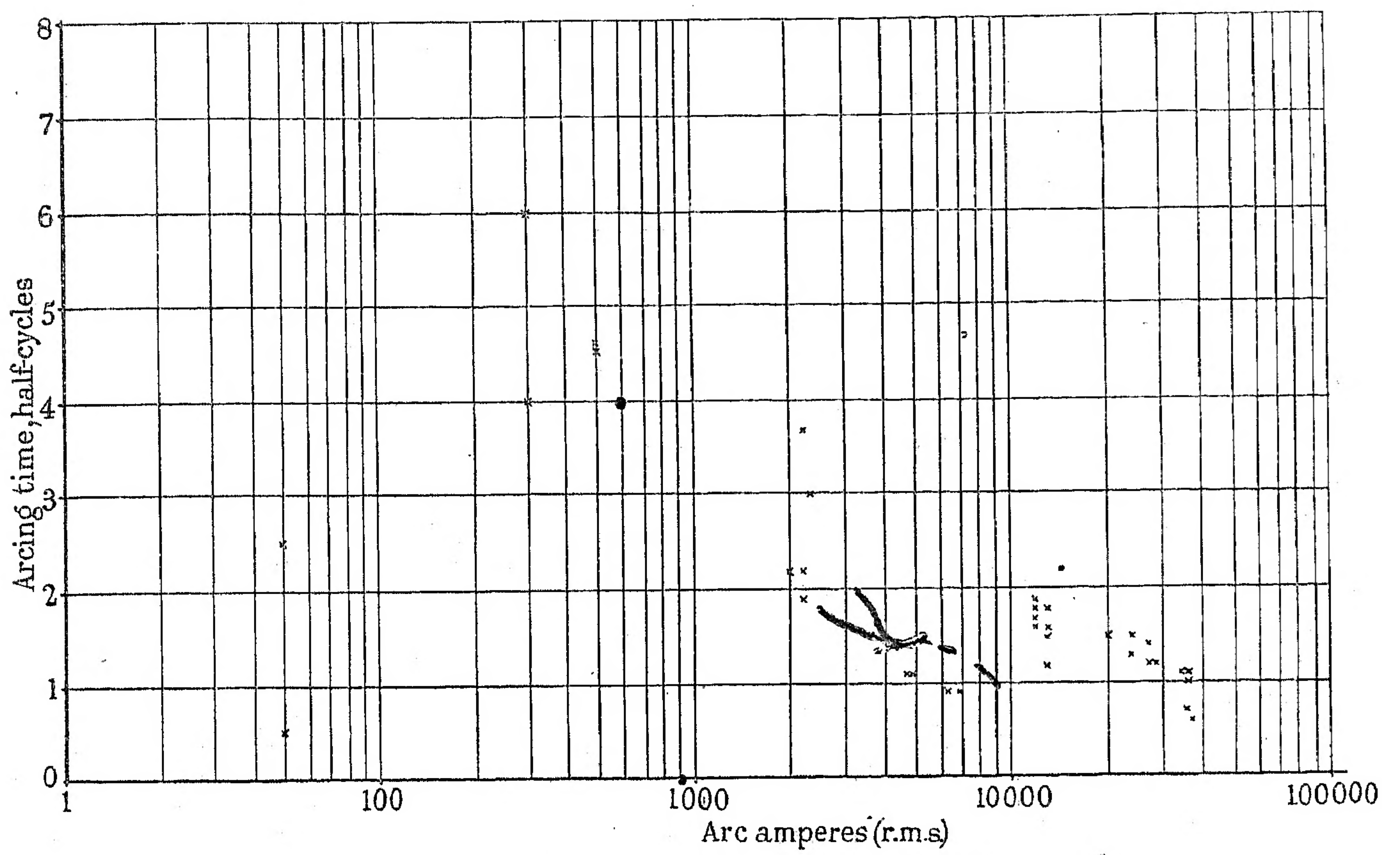


Fig. 8.—Performance of 400/660-volt air circuit-breaker.

out, thus putting the oil into compression. The characteristic of such a dashpot is shown in Fig. 7.

Breakers fitted with such dashpots can be made to discriminate one against another, and against any high-rupturing-capacity fuses which may be installed in series.

PERFORMANCE TESTS

Fig. 6 (Plate 1) shows a breaker designed for 35 MVA at 660 volts, 3-phase, or 25 MVA at 400 volts, 3-phase. This is equivalent to 36 000 amperes (r.m.s. symmetrical) breaking current and 92 000 amperes (peak) making capacity.

Fig. 8 shows the arcing time plotted against the short-circuit current, whilst Table 1 reproduces test-results incorporating 3-unit duty cycles as specified in B.S. No. 116—1937.

Theoretical considerations suggest, and actual tests show, that breakers of this type have a practically consistent short-circuit current rating independent of voltage. This means that the rupturing capacity in kVA varies directly as the voltage. Thus, the breaker shown has a rating of 36 000 r.m.s. amperes, equivalent to 15 MVA at 230 volts, 25 MVA at 400 volts, or 35 MVA at 660 volts.

Fig. 9 shows the curve of total break time plotted against short-circuit current. The total break time is measured from the moment of energizing the trip coil until the arc is finally cleared.

A similar breaker was subjected to the following tests on an 800-volt 3-phase low-power-factor circuit: Make and break 1 400 amperes 1 000 times; make 400 amperes, break 250 amperes, 200 times; open and close on no-load 800 times. At the conclusion of these tests the contacts showed only slight burning, not more than 0·010 in. deep, whilst the arc chutes showed no erosion.

Fig. 10 (Plate 1) shows a photograph of the contacts after the tests.

This characteristic performance of the air circuit-breaker makes it eminently suitable for controlling rolling-mill motors and similar duties.

For this type of duty the oil circuit-breaker cannot be

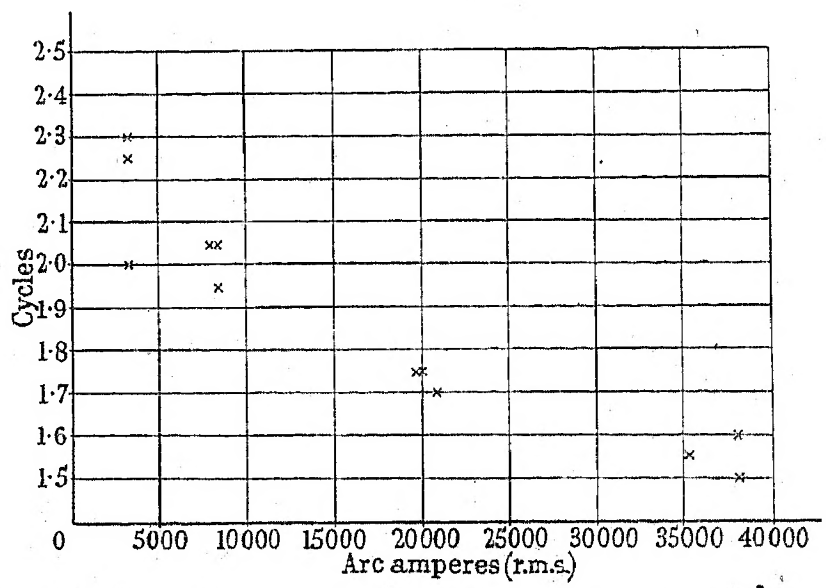


Fig. 9.—Total break times at 440 volts for 800-amp. air circuit-breaker.

compared with the air circuit-breaker. For the same amount of contact erosion, the oil breaker could only perform from one-twentieth to one-fiftieth the number of operations.

HIGH-RUPTURING-CAPACITY FUSES

General

High-rupturing-capacity fuses up to 600 amperes continuous rating are now available. These fuses can

Table 1

SHORT-CIRCUIT TESTS APPLIED TO AIR-BREAK CIRCUIT-BREAKER (TOTALLY ENCLOSED)

400 volts, 25 MVA, 36 000 amperes (symmetrical), 92 000 amperes (peak) making; or 660 volts, 35 MVA, 31 000 amperes (symmetrical), 80 000 amperes (peak) making

Item No.	Duty	Test voltage		Current (amp.)			Arc duration (half-cycles)	Total break time (sec.)	MVA interrupted
		Applied volts	Recovery volts	Maximum peak in first half-cycle	Initial in arc				
					Symm.	Asym.			Symm.
1*a*	B 3 min.	685	666	68 000 86 000 63 600	31 800 30 400 31 200	31 800 30 400 31 200	1·3 1·1 1·3.	0·058	35·9
1*b*	B 3 min.	706	655	63 500 84 600 69 600	31 800 31 000 31 200	31 800 31 000 31 200	1·3 0·93 1·3	0·039	35·5
1*c*	B	706	664	79 500 65 600 60 600	31 800 31 000 31 200	31 800 31 000 31 200	1·0 1·4 1·4	0·042	35·9
2*a*	B 3 min.	476	454	81 900 93 400 56 900	37 200 36 800 35 900	37 200 36 800 35 900	1·3 1·0 1·3	0·035	28·8
2*b*	MB 3 min.	476	443	67 700 90 500 82 200	37 200 37 100 35 900	37 200 37 100 35 900	1·0 1·0 0·97	0·033	28·2
2*c*	MB	476	440	88 200 61 200 77 800	37 200 36 800 35 300	37 200 36 800 35 300	1·0 1·0 0·97	0·033	27·8
3*a*	B 3 min.	453	447	85 000 55 500 74 800	36 900 36 800 33 200	37 200 36 800 34 100	1·0 1·1 1·1	0·031	27·5
3*b*	B 3 min.	461	457	81 900 59 800 82 200	39 100 38 200 36 500	39 400 38 200 37 100	1·1 0·96 1·1	0·032	30·0
3*c*	B	468	449	78 800 65 600 86 700	40 000 37 100 36 500	40 500 37 100 37 700	0·94 0·94 0·80	0·030	29·4
4*a*	B 3 min.	453	428	38 400 52 400 43 200	20 300 19 100 19 500	20 300 19 300 19 500	1·1 1·4 1·4	0·035	14·5
4*b*	B 3 min.	476	450	42 100 54 900 44 100	21 600 21 000 20 800	21 600 21 000 20 800	1·3 1·2 1·3	0·034	16·5
4*c*	B	461	438	40 200 53 200 45 000	20 700 19 800 19 500	20 700 19 800 19 500	1·4 1·2 1·4	0·035	15·2

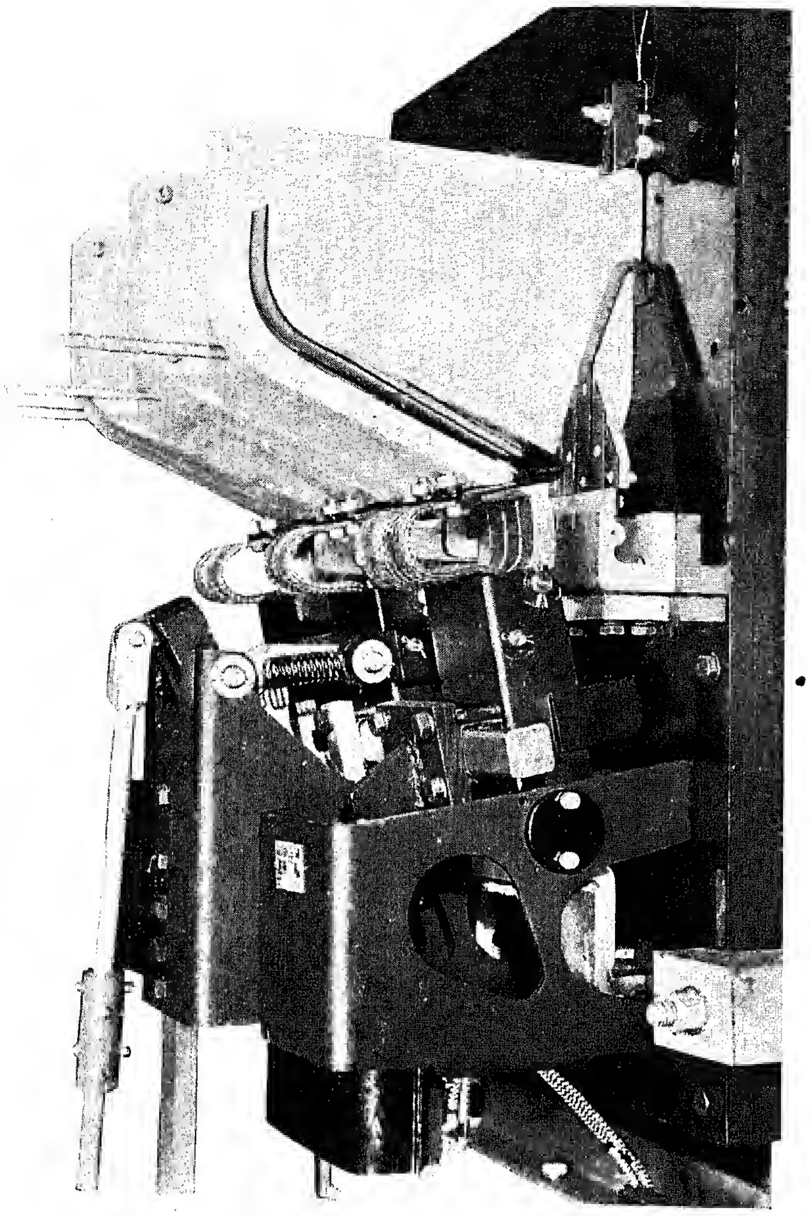


Fig. 4.—Three-phase air circuit-breaker, showing slit arcing horns.

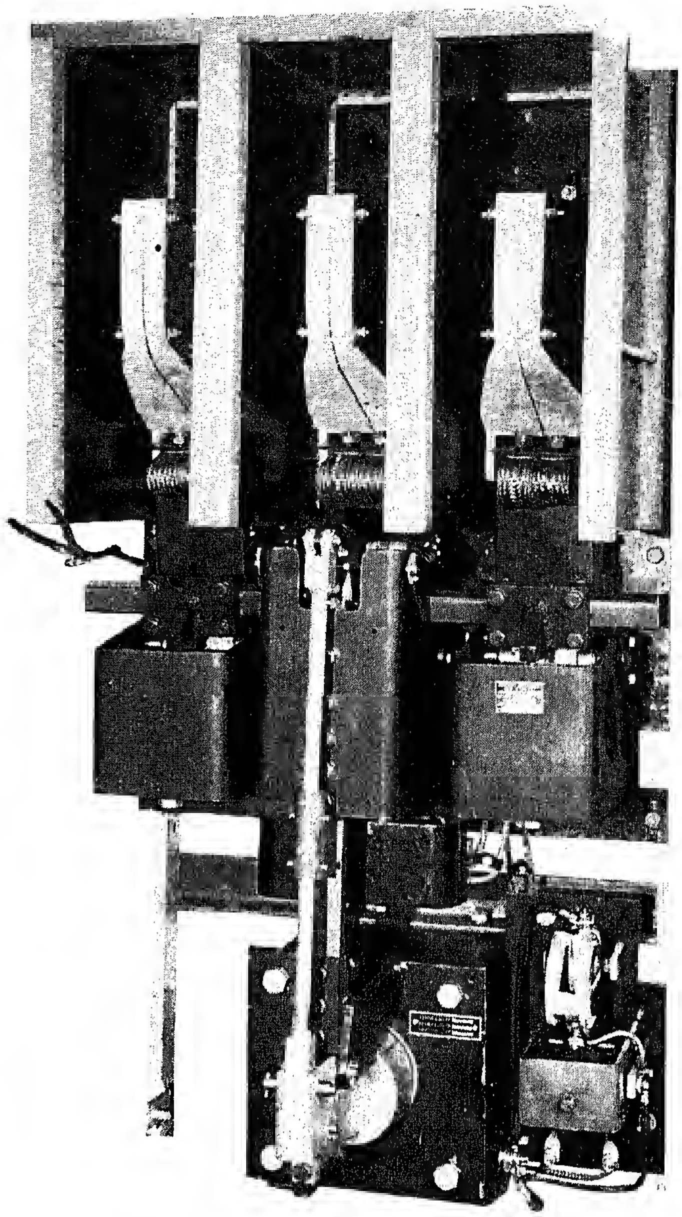


Fig. 6.—Three-phase air circuit-breaker, showing phase barriers.

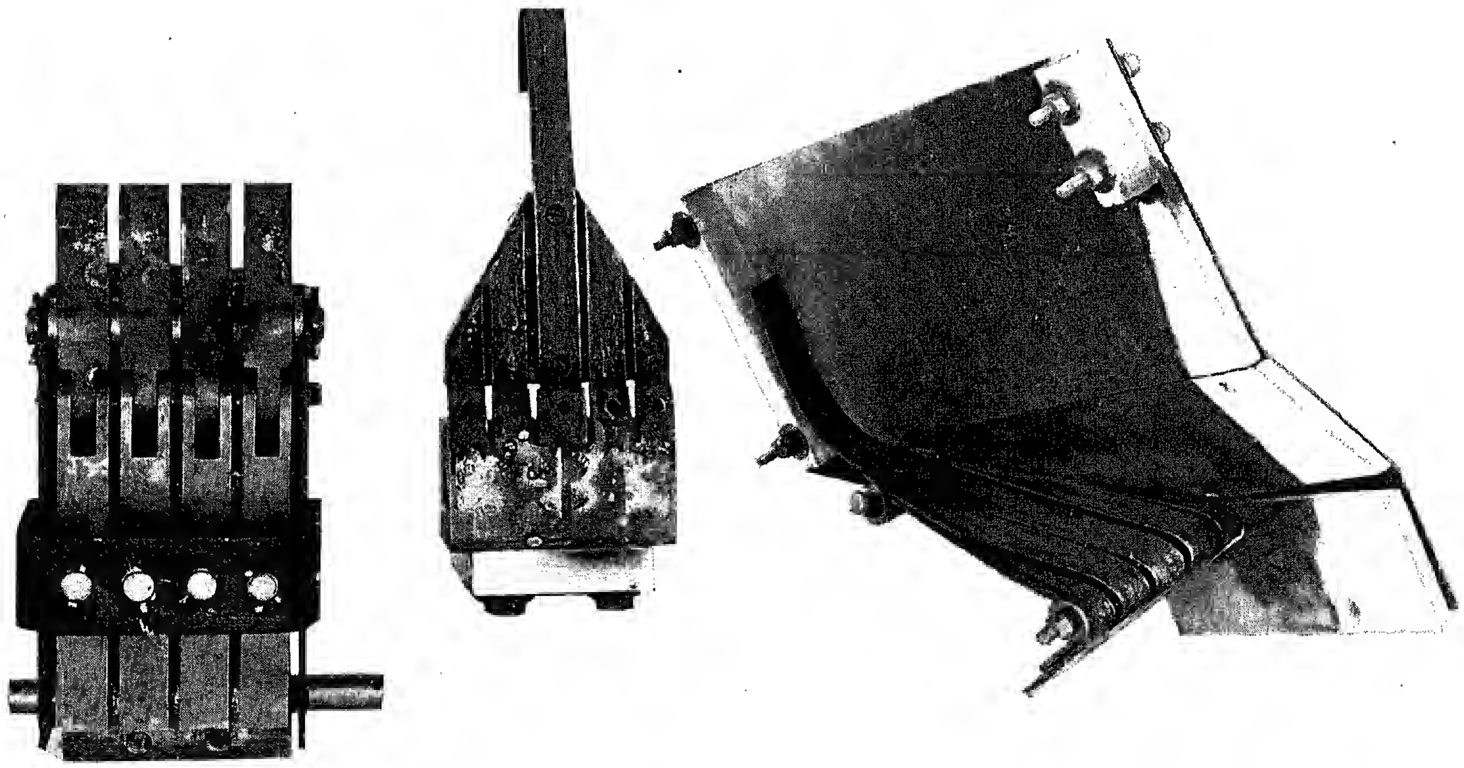


Fig. 10.—Contacts after load making and breaking tests.

Plate 2

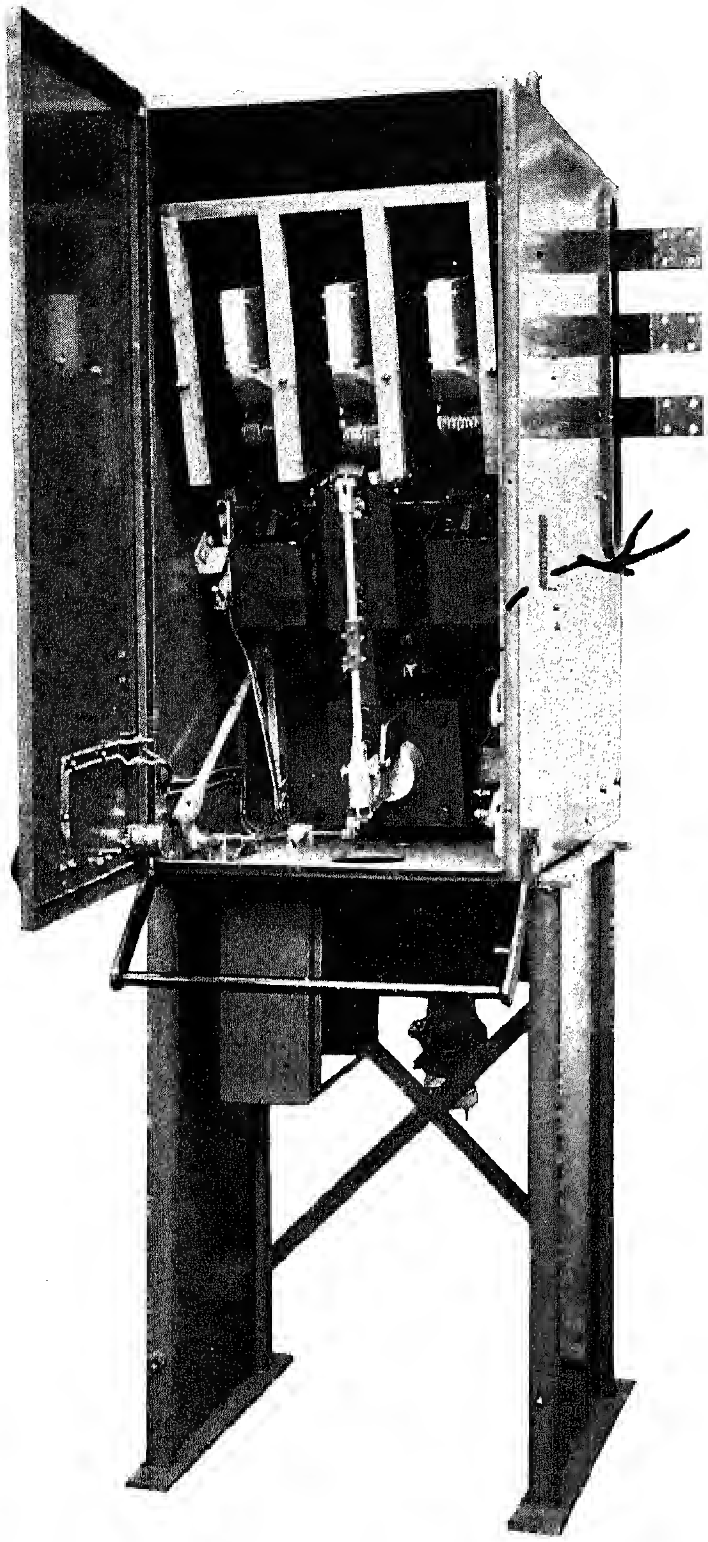


Fig. 13.—Typical solenoid-operated air-circuit-breaker equipment.

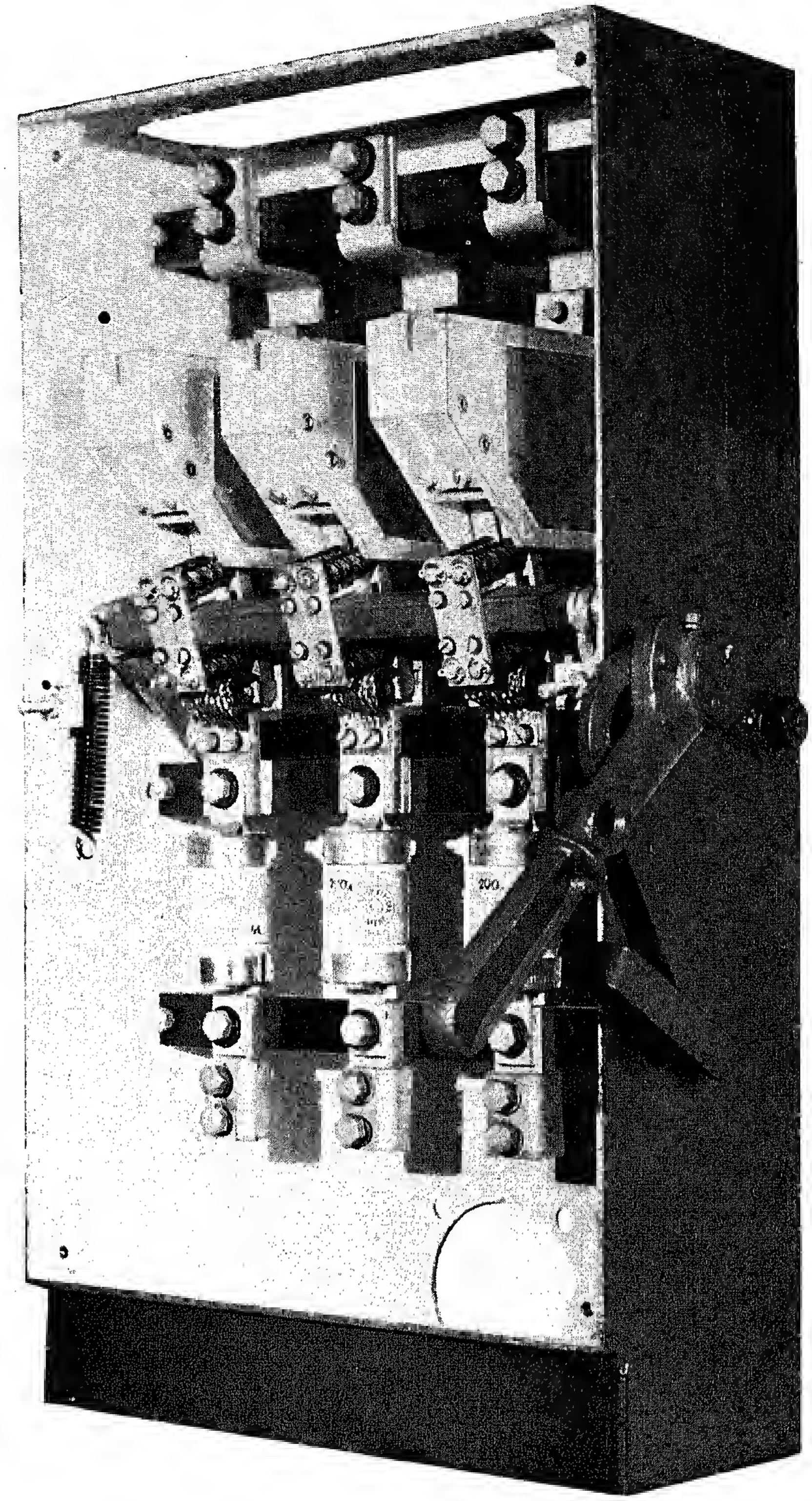
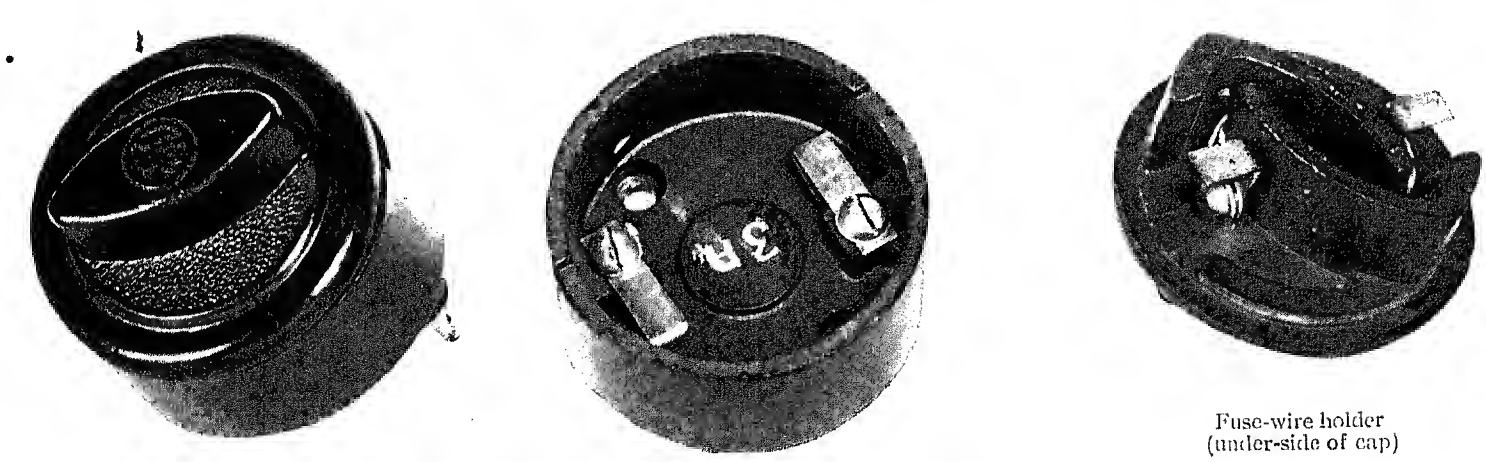


Fig. 16.—200-amp. switch-fuse: cover removed.



Fuse complete

Base

Fuse-wire holder (under-side of cap)

Fig. 11.—10-amp. high-rupturing-capacity rewireable fuse.

Table 1 (*contd.*)

Item No.	Duty	Test voltage: Applied volts	Test voltage: Recovery volts	Current (amp.): Maximum peak in first half-cycle	Current (amp.): Initial in arc: Symm.	Current (amp.): Initial in arc: Asym.	Arc duration (half-cycles)	Total break time (sec.)	MVA interrupted: Symm.
5*a*	B	484	462	15 900 23 000 18 900	8 400 8 110 8 150	8 400 8 110 8 150	1·3 1·5 1·5	0·041	6·59
	3 min.								
5*b*	B	484	462	19 900 13 900 21 400	8 320 7 950 7 980	8 320 7 950 8 060	1·7 1·8 1·8	0·041	6·46
	3 min.								
5*c*	B	484	462	13 300 20 100 21 400	8 320 8 110 8 150	8 320 8 110 8 150	1·5 1·5 1·5	0·039	6·59
6*a*	B	695	669	8 390 7 490 10 500	3 950 3 830 3 830	3 980 3 860 3 970	2·1 1·7 2·1	0·053	4·48
	3 min.								
6*b*	B	706	679	8 720 7 490 10 700	3 950 3 830 3 900	3 980 3 830 3 970	1·8 2·0 2·0	0·052	4·57
	3 min.								
6*c*	B	695	644	5 760 9 820 9 830	3 950 3 760 3 900	3 950 3 800 3 930	2·1 1·9 2·1	0·053	4·32
7*a*	B	468	449	8 440 8 490 5 630	3 300 3 460 3 510	3 340 3 500 3 510	1·8 2·0 2·0	0·046	2·66
	3 min.								
7*b*	B	461	449	8 620 6 330 8 000	3 380 3 430 3 510	3 410 3 430 3 510	1·7 1·7 1·3	0·045	2·67
	3 min.								
7*c*	B	461	441	8 440 8 320 5 630	3 300 3 430 3 440	3 340 3 430 3 440	1·5 1·5 1·4	0·040	2·59
8	M	494	—	101 000 66 400 84 200	— — —	34 900 36 700 34 300	} Mean value over 1 sec.		

be used on circuits with a prospective short-circuit current up to 36 000 r.m.s. amperes at 440 volts with perfect safety.

For circuits rated up to 10 amperes, open fuse-wires in insulation holders are quite satisfactory provided care is taken to prevent the metal vapour and arc gas striking to earth or between phases. Fig. 11 (Plate 2) shows a fuse which has been designed with this point in view.

For circuits rated above 10 amperes it is necessary to resort to the cartridge form of fuse, in which the current is carried by many parallel elements, all embedded in an arc-quenching powder. As already mentioned, these fuses act so quickly that the short-circuit current is cut off by the fuse before it reaches its maximum or prospective value. Table 2 gives typical values and has been compiled by examining a large number of test results.

Table 2

PEAK CURRENT PASSED BY FUSE, AND DURATION OF SHORT-CIRCUIT, FOR HIGH-RUPTURING-CAPACITY FUSES TESTED IN CIRCUITS WITH PROSPECTIVE SHORT-CIRCUITS OF 25 MVA AT 440 VOLTS

Normal fuse rating	Peak current	Duration of short-circuit
amp.	amp.	sec.
15	3 000	0·003
30	3 500	0·003
50	5 000	0·003
60	7 000	0·003
80	9 000	0·004
100	12 000	0·006
125	15 000	0·006
160	20 000	0·008
200	24 000	0·010
300	30 000	0·012
350	35 000	0·013
400	40 000	0·014

Use on Circuits of Low Current-Carrying Capacity

It is now quite common to have motors as small as 5 h.p. connected on to a system with a short-circuit rating of 25 MVA. Such a motor could be controlled by a circuit-breaker rated at 10 amperes, fitted with 10-ampere thermal trips. This breaker would not interrupt an r.m.s. short-circuit current in excess of 200 amperes, whereas the circuit can deliver up to 36 000 r.m.s. amperes and 92 000 peak amperes. When a 30-ampere high-rupturing-capacity fuse is placed in series with such a breaker, the current-limiting effect of the fuse limits the short-circuit current to within the through-current capacity of the breaker.

NON-AUTOMATIC SWITCHES FOR USE IN SWITCH-FUSES

A large number of circuits, such as lighting, heating, and feeders to distribution boards and groups of motors and, in special cases, direct-on-line starting induction motors, can be controlled by switches in series with high-rupturing-capacity fuses without any further automatic features. For many of these circuits the ordinary switch-fuse, capable of making and breaking only $1\frac{1}{2}$ times its continuous rated current, is quite inadequate.

Large incandescent electric lamps have a current inrush of 7 to 10 times the final current and, when inching direct-on-line starting induction motors, up to 10 times full-load current may have to be made and broken. The switch must also be capable of making and carrying the short-circuit current permitted by the maximum size of fuse that can be accommodated in the switch-fuse. The effect of this is to convert the switches to the equivalent of non-automatic circuit-breakers with a low ratio of rupturing capacity to normal continuous current rating. These have to be designed to meet the following conditions. First, they must be able to meet their making-capacity rating without blowing-off or undue burning. Secondly, they must be such that an inherent arc blow-out effect is obtained without any multi-turn blow-out coils. Thirdly, they must carry their continuous rating without overheating.

A form of contact which meets these requirements is shown in Fig. 12. Magnetic blow-off forces are kept to a minimum by keeping the dimensions AF and AE small. Above 10 000 (peak) amperes, multi-contacts are used to sub-divide the current. The good current making and breaking characteristics are obtained by using butt contacts with a wiping action upon closing. Hooking

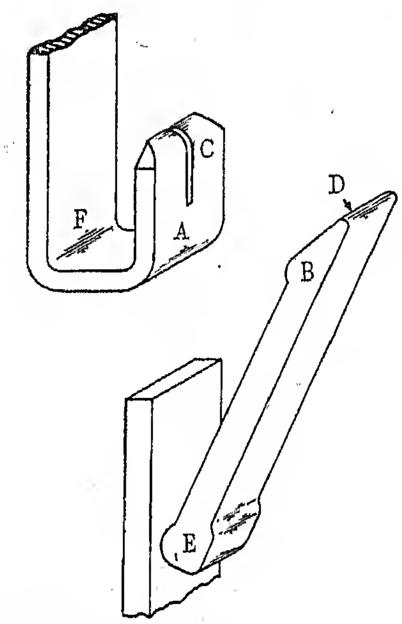


Fig. 12.—Contacts for switch-fuse.

the copper contact back on to itself ensures that arcs which start at AB travel up to CD.

ARC CHUTES

Exactly the same considerations apply to the design of arc chutes as apply to the larger circuit-breakers already described, except that they can be scaled down to deal with the smaller currents.

SWITCH-FUSE MECHANISMS

Whilst the quick-make/quick-break mechanisms which are very common on low-duty switch-fuses are satisfactory for certain applications, they are not suitable for the high-duty switch-fuse with which this paper deals. Such mechanisms fail because they are unable to force the contacts right home when they have been burned by repeated current making and breaking. This failure is due to the roughening and presence of copper beads. Many cases are on record where the switches have been entirely wrecked through beads on one contact holding the other faces so that they are only just touching, with resultant continuous arcing from the load current. A better type of mechanism is that in which the circuit is positively made under the control of the operator but has a quick-break feature. This is the arrangement which has been used universally on hand-operated oil circuit-breakers.

Table 2

PEAK CURRENT PASSED BY FUSE, AND DURATION OF SHORT-CIRCUIT, FOR HIGH-RUPTURING-CAPACITY FUSES TESTED IN CIRCUITS WITH PROSPECTIVE SHORT-CIRCUITS OF 25 MVA AT 440 VOLTS

Normal fuse rating	Peak current	Duration of short-circuit
amp.	amp.	sec.
15	3 000	0·003
30	3 500	0·003
50	5 000	0·003
60	7 000	0·003
80	9 000	0·004
100	12 000	0·006
125	15 000	0·006
160	20 000	0·008
200	24 000	0·010
300	30 000	0·012
350	35 000	0·013
400	40 000	0·014

Use on Circuits of Low Current-Carrying Capacity

It is now quite common to have motors as small as 5 h.p. connected on to a system with a short-circuit rating of 25 MVA. Such a motor could be controlled by a circuit-breaker rated at 10 amperes, fitted with 10-ampere thermal trips. This breaker would not interrupt an r.m.s. short-circuit current in excess of 200 amperes, whereas the circuit can deliver up to 36 000 r.m.s. amperes and 92 000 peak amperes. When a 30-ampere high-rupturing-capacity fuse is placed in series with such a breaker, the current-limiting effect of the fuse limits the short-circuit current to within the through-current capacity of the breaker.

NON-AUTOMATIC SWITCHES FOR USE IN SWITCH-FUSES

A large number of circuits, such as lighting, heating, and feeders to distribution boards and groups of motors and, in special cases, direct-on-line starting induction motors, can be controlled by switches in series with high-rupturing-capacity fuses without any further automatic features. For many of these circuits the ordinary switch-fuse, capable of making and breaking only 1½ times its continuous rated current, is quite inadequate.

Large incandescent electric lamps have a current inrush of 7 to 10 times the final current and, when inching direct-on-line starting induction motors, up to 10 times full-load current may have to be made and broken. The switch must also be capable of making and carrying the short-circuit current permitted by the maximum size of fuse that can be accommodated in the switch-fuse. The effect of this is to convert the switches to the equivalent of non-automatic circuit-breakers with a low ratio of rupturing capacity to normal continuous current rating. These have to be designed to meet the following conditions. First, they must be able to meet their making-capacity rating without blowing-off or undue burning. Secondly, they must be such that an inherent arc blow-out effect is obtained without any multi-turn blow-out coils. Thirdly, they must carry their continuous rating without overheating.

A form of contact which meets these requirements is shown in Fig. 12. Magnetic blow-off forces are kept to a minimum by keeping the dimensions AF and AE small. Above 10 000 (peak) amperes, multi-contacts are used to sub-divide the current. The good current making and breaking characteristics are obtained by using butt contacts with a wiping action upon closing. Hooking

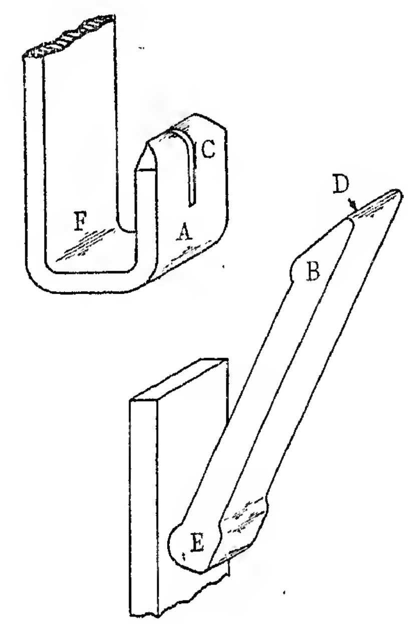


Fig. 12.—Contacts for switch-fuse.

the copper contact back on to itself ensures that arcs which start at AB travel up to CD.

ARC CHUTES

Exactly the same considerations apply to the design of arc chutes as apply to the larger circuit-breakers already described, except that they can be scaled down to deal with the smaller currents.

SWITCH-FUSE MECHANISMS

Whilst the quick-make/quick-break mechanisms which are very common on low-duty switch-fuses are satisfactory for certain applications, they are not suitable for the high-duty switch-fuse with which this paper deals. Such mechanisms fail because they are unable to force the contacts right home when they have been burned by repeated current making and breaking. This failure is due to the roughening and presence of copper beads. Many cases are on record where the switches have been entirely wrecked through beads on one contact holding the other faces so that they are only just touching, with resultant continuous arcing from the load current. A better type of mechanism is that in which the circuit is positively made under the control of the operator but has a quick-break feature. This is the arrangement which has been used universally on hand-operated oil circuit-breakers.

GENERAL PRINCIPLES OF SWITCHGEAR DESIGN

Before the unit apparatus previously described can be applied to industry, it is necessary to collect and assemble the components into complete switchgear equipments, which, in turn, must be suitable for assembling into various combinations thus forming complete switchboards.

Apart from the requirements of each component piece of apparatus, the majority of which are allied to performance, certain general principles of switchgear design have been firmly established by experience. Such principles, whilst varying in some degree dependent on type, service, and duty of the switchgear, can be reduced to fundamentals and, in the specific class of gear with which this paper is concerned, can be defined as follows: (*a*) Enclosure of live parts; (*b*) safety of operation; (*c*) ease of maintenance; (*d*) minimum hazard to adjacent apparatus.

Enclosure of Live Parts

The entire equipment should have all live parts enclosed in an earthed metal casing which is substantially dust-proof, moisture-proof, and vermin-proof. This renders the gear suitable for installation in any industrial location with the exception of positions where explosive atmospheres occur.

Safety of Operation

The first requirement of safety of operation is met by total enclosure, but this should be supplemented by interlocks to ensure that operations are carried out in the correct sequence and that access for maintenance to parts normally alive can be obtained only after proper isolation.

Such interlocks should provide for the following:—

(i) Access to the circuit-breaker or fuses should not be obtainable until they are completely isolated.

(ii) In equipments incorporating circuit-breakers, it should not be possible to operate the isolating devices unless the circuit-breaker is open.

(iii) Once the door giving access has been opened, it should not be possible to close the isolating device until the door is reclosed.

(iv) The breaker cannot be operated unless the isolating device is either fully "open" or fully "closed."

Ease of Maintenance

(i) Where fuses are fitted, they should be readily replaceable when blown.

(ii) Where breakers are fitted, they should be so arranged that they can be closed or opened either in the alive or in the isolated position. In the case of electrically-operated breakers, this should also apply to the emergency hand operating gear.

(iii) Where isolation is obtained by plugging the breaker, the breaker should be readily removable from its cubicle.

Minimum Hazard to Adjacent Apparatus

The complete absence of oil and the use of free air as an insulating medium reduces fire hazard to a minimum. In addition, effective gas barriers between the busbar chambers of adjacent equipments are essential to prevent any possibility of arcs spreading between equipments. Each compartment, e.g. circuit-breaker busbar chamber, and air circuit-breaker, should be effectively separated from its neighbours, thus localizing any possible damage due to electrical faults.

Where breakers are fitted, effective arc barriers between phases of the breaker are essential and should be formed from continuous sheets of insulation, suitably supported, to prevent arc-over between phases.

To disperse any gas products and prevent any possibility of rise in pressure inside the containing case, spring-loaded pressure-relief vents should be incorporated in the top of the circuit-breaker compartment set to open at a pressure value determined by test. It is interesting to note that such vents have proved extremely satisfactory under actual full-scale test conditions.

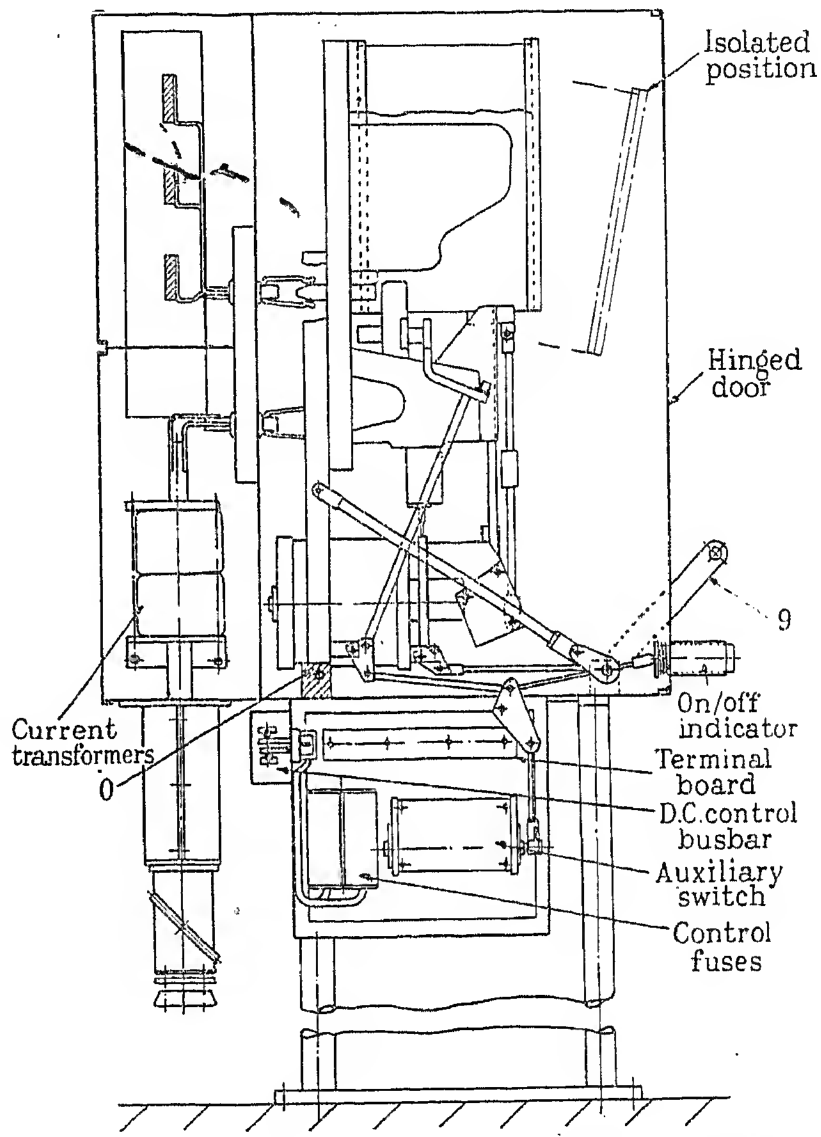


Fig. 14.—Sectional view of solenoid-operated equipment.

Examples of Equipments

A complete solenoid-operated air circuit-breaker equipment which meets these requirements is shown in Fig. 13 (Plate 2), whilst Fig. 14 shows the cross-section. It will be noticed that all live parts are enclosed in a sheet-steel housing provided with dustproof covers to the busbar and circuit chambers and a dustproof door to

the circuit-breaker compartment. The circuit-breaker is mounted on a panel and is isolated by hinging forward about the pivot O by the handle (9), thus unplugging it from the busbars and circuit. The handle (9) interferes with the door, so that it cannot be opened until the handle is lowered, and once the door is open the handle cannot again be raised. This equipment is rated at 25 MVA at 400 volts.

These air circuit-breakers can be very simply adapted to double-busbar equipments. Fig. 15 shows a cross-

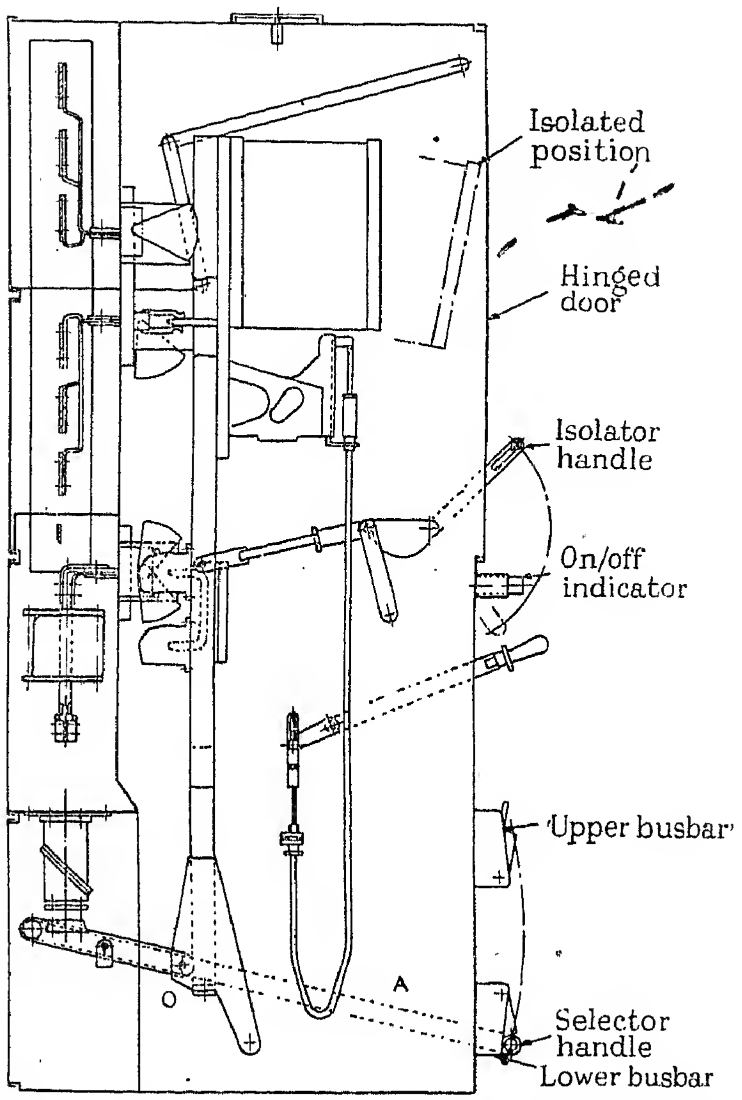


Fig. 15.—Sectional view of hand-operated double-busbar equipment plugged on to lower busbars (interlock not shown).

section of such an equipment. As before, isolation is obtained by hinging the breaker forward about the hinge point O. In this case, however, the hinge point O is pivoted on the lever arms A, so that when the breaker is in the unplugged position it can be bodily raised or lowered to bring it opposite either the lower or the upper busbar, thus effecting busbar selection.

A complete switch-fuse unit embracing a 200-ampere non-automatic air-break switch and high-rupturing-capacity fuses is shown in Fig. 16 (Plate 2). When the cover is on, the case is divided into two compartments by an insulating barrier, the switch being located in one part and the fuses in the other, access to the latter compartment being obtained through a hinged-front lid. The operating handle is brought to the outside of the case, all live parts being enclosed and the necessary interlocks provided to ensure complete safety to the operator. The proportions of the closing mechanisms and the design of electrical contacts allow the switch to be closed safely on to a fault having a prospective short-circuit current equivalent to 25 MVA.

The chief essential in this class of gear is the rapid replacement of blown fuse-links; and safe, easy, access to the fuse-link compartment must be provided. The use of thumbscrew versus standard nut connections for the fuse-links is debatable, there being arguments for each school of thought. Effective barriers between phases of the actual contacting members of the switch are provided by the arc chutes associated with each phase, whilst the busbar supports between equipments provide effective barriers which, by preventing the spreading of gas, restrict faults to the originating equipment.

No actual barriers are required between the high-rupturing-capacity fuse-links; such fuses, being of the filled and shielded type, act as their own barriers. Repeated short-circuit testing of such devices has proved their ability to function correctly and quietly, with no tendency to produce external flame or gas.

The busbar chambers for use with these switch-fuses, which are of unit construction and are bolted together, are supported either by floor-mounting pedestals or by wall-mounting brackets and form a self-supporting structure. The switch and fuse units are bolted either above or below the busbars, the position being dictated by the layout required.

Instruments can be accommodated in specially shaped attachments which fit either above or below the units, depending upon requirements. Where the switch-fuse unit is required for motor starting, it is preferable to incorporate an additional switch to act as busbar isolator, thus allowing the motor starting switch and the fuses to be examined and maintained without shutting down the busbars.

DISCRIMINATIVE PROTECTION

In order to obtain discrimination between air circuit-breakers controlling incoming circuits or outgoing feeders and switch-fuses controlling individual pieces of apparatus, it is necessary to ensure that the air circuit-breakers have a definite minimum time-delay, even at the full system short-circuit current. In general, this requirement is not met by time-delay fuses shunting direct-acting trip coils or by suction disc or dashpot time-lag devices, as these all tend to become instantaneous on short-circuit, even when due allowance is made for the saturation of current transformers in the former case.

It has been usual to overcome this difficulty by fitting induction overload relays operated by current transformers. A much more economical, although slightly less flexible, arrangement, is to use compression-type oil dashpots in which the dashpot plunger is forced into the pot instead of being pulled out. This means that, however great the tripping force, the oil must be forced

past the plunger and it is not possible for the plunger to be pulled out instantaneously by pulling a vacuum between its lower surface and the oil.

As has already been pointed out in the paper, whenever such devices are fitted the breaker should be able to make and hold its rated short-circuit current for a period of not less than 1 sec.

ACKNOWLEDGMENTS

The authors wish to acknowledge their indebtedness to the British Thomson-Houston Co., Ltd., for permission to publish the information given in this paper; and to members of the Switchgear Department of the firm who helped with the experimental work on which the designs are based.

DISCUSSION BEFORE THE INSTITUTION, 7TH MARCH, 1940

Mr. J. O. Knowles: The authors, in their Introduction, express some fear that engineers may be indifferent to the problems of l.v. switchgear design, but this subject is nowadays attracting increasing attention. During the past few months I have had a number of letters, from engineers in various parts of the country, which I think typical of increasing interest in the development of air-break l.v. circuit-breakers.

I hope that the authors will not let their enthusiasm for air-break switchgear induce them to advocate l.v. circuit-breakers of 4 000 amperes and 50 000 kVA, in new installations at least. While such gear is feasible, it is not desirable.

I should like to point out that it is not good industrial practice to allow main l.v. breakers to remain untripped on short-circuit for periods up to 5 sec. Conditions are different in power-station work, where the breakers may remain untripped during disturbances on the line, caused by short-circuits elsewhere on the h.v. gear, which have caused a severe drop of voltage. Low-voltage gear is most commonly installed in proximity to personnel, and when a short-circuit occurs on the load side of the l.v. switchgear such arc energy can be developed in a subsidiary circuit such as the cast-iron cover of a small distribution switch that this may be blown to the other end of the room. From the point of view of the safety of personnel and of restarting without major damage it is better for the back-up circuit-breaker to trip before the expiry of 5 sec., even if this means making a restart after having cut out the faulty section. In some places in connection with process work, etc., this interruption may be very undesirable, but even then the design of the protective gear should be carefully reviewed to see whether sufficient discrimination cannot be obtained without such a long time-delay.

The authors point out that on short-circuit rating the arc energy depends upon the current and time only, and not upon the circuit voltage. I should be glad if they could give a more mathematical treatment of that point. One cannot ignore, in general, the effect of the arc voltage, particularly when the arc is not under such definite control as it is in the circuit-breakers of which the authors speak. Low-voltage gear is often sold in three voltage sizes, namely 230, 440 and 660 volts, and 400-volt gear is not necessarily suitable for 660-volt working. The authors appreciate the difference between "scaling down," as from 660 volts to 440 volts, and "scaling up," as in the following example: Assuming a single contact has a current-carrying capacity of 200 amperes, four such contacts in parallel have not a capacity of 800 amperes owing to the difference in millivolt drop between the various contacts, but if four contacts will carry 800 amperes one contact will (as the authors say) carry 200 amperes easily.

Would the authors advocate a 400-ampere oil-less circuit-breaker for 25 000 kVA? If such a breaker were allowed to trip instantaneously on short-circuit I think it would be satisfactory.

The authors state that Group 1 circuit-breakers have an economic rupturing capacity of 15 to 20 times the full-load capacity; I would mention that miniature breakers have been placed on the market which have been tested up to 2 000 amperes.

The authors speak of these small Group 1 circuit-breakers as having a total life of more than 10^6 operations, and a contact life of less than 10^3 operations. It is clear that the authors refer primarily to circuit-breakers rather than contactors, the former being designed for relatively infrequent operation and the latter for relatively frequent operation. While the borderline may be indistinct, the two types are often complementary and both may be built-up into the same switchboard.

Referring to Fig. 1, I should like to know whether any means of adjustment of the toggle mechanism is provided.

Turning to the contact arrangements shown in Figs. 1 and 2, I see that the main circuit is carried through the pin underneath the rocker pin, and I think there is some doubt as to whether this would be satisfactory in all respects. If the circuit-breaker is very infrequently operated with currents of the order of 800 amperes and upwards, there is the possibility of eventual overheating at the butt joint near the pin. Also, wear is liable to occur on the pin under conditions of frequent operation.

I must assume that the braids shown in Fig. 3 will have to withstand short-circuit forces momentarily. Also, are the arcing contacts easily accessible?

The U-shaped phase barriers shown in Fig. 6 seem to be almost an afterthought. The authors suggest that under the influence of these U-shaped barriers the arc will be diverted downwards, but it seems to me that it is much more likely to come out at the front. It would be interesting to know whether on the higher-voltage systems the authors have found it necessary to line the front of the case as well.

With regard to the switch-fuse shown in Fig. 16 (Plate 2), were iron cheeks fitted to the switch barriers to prevent the arc from blowing downwards? The fuses in these switch-fuses should not be run too close to their minimum fusing current, in view of the proximity of the fuse terminals to the butt-contact on the switches. The authors' statement that the switch-fuses are "positively made under the control of the operator" means that "the switches are of the slow-make type," and, as such, they appear to me to be preferable to butt-contact

switches with a quick-make action, because the latter would be subject to "bounce" on the butt contacts. What is the rupturing capacity of the small rewirable fuses in Fig. 11?

With regard to maintenance, in the equipments shown in Figs. 14 and 15 I should have preferred the spring isolator contacts to have been on the movable portion, particularly on duplicate-busbar equipments, where it must be difficult to renew the springs without shutting down the busbars. Moreover, questions of overheating are important under the heavy-current conditions in which these circuit-breakers are to be used, and this is particularly so where users are apt to leave the isolator plugs in contact from one year's end to the next.

Mr. J. W. Leach: My experience of distribution in densely loaded areas confirms that short-circuit values of 25 000 kVA have to be met, but that a breaker which will meet that duty in association with high-rupturing-capacity fuses for the distribution network, and cut-outs on consumers' premises, will be adequate for the conditions likely to arise for a very long time ahead.

The breaker described in the paper appears to have small space and head-room factors. It is therefore particularly suitable for use in densely loaded areas where space is restricted and valuable, and thus supplies a long-felt need.

How close can earthed metal be mounted in front of such a breaker? This question has some bearing on manual operation of the breaker.

A compression type of dashpot has been developed and used by my own staff with excellent results; it has given a great improvement in discrimination at times of heavy faults.

Have the authors any figures indicating the degree of stability on through faults and the degree of accuracy on overload time settings for these circuit-breakers?

I assume that the statement on page 462 concerning repeated closing above normal full-load rating does not apply to Group 3 breakers.

I do not altogether agree with the statement (page 470) that it is now quite common to have motors as small as 5 h.p. connected to a system with a short-circuit rating of 25 MVA; in most cases the intermediate small cable connections will reduce the short-circuit current, and the number of such motors must be very small. In my opinion it is not necessary to use fuses in association with Group 1 breakers.

I gather that the authors have conducted tests on breakers with high-rupturing-capacity fuses, and I assume that the items were connected in series. Have fuses been blown out of their holders in any of these tests?

It would be interesting to know whether the breakers referred to on page 467 have pressure line contacts.

With regard to the assembly of the board shown in Fig. 16 (Plate 2), could the fuses be put between the breaker and the busbar? If this were done it would be possible to use the fuses as isolating links.

In conclusion, I would say that wherever a satisfactory air circuit-breaker is available it should be used in preference to an oil circuit-breaker on the grounds of economy in maintenance and initial costs, less space occupied, and smaller fire risk.

Mr. R. T. Lythall: I am pleased that in the Introduction the authors draw attention to the relation which exists between MVA and voltage in determining the severity of duty. Almost every day I come across cases in which reference is made to 25 MVA with some indifference, as if such a rating were easy of accomplishment by designers. The inability of many users to think in terms of current is, I think, entirely responsible for this situation. It would be an excellent thing if in B.S. No. 116—1937 and the new low-voltage Specification which is now in course of preparation the ratings could be expressed in terms of current. Such a change would eliminate arguments as to the ability of a circuit-breaker, tested at one voltage, to act at a lower voltage. Within reasonable limits it should be clear that a circuit-breaker proved capable of clearing x amperes at one voltage, should be equally successful in clearing the same current at a lower voltage.

The authors claim that the results of failure with low-voltage breakers may be less spectacular than the results of failure with high-voltage breakers. My view is that few low-voltage breakers fail in a spectacular manner, if at all, as the result of *breaking* on short-circuit. The greatest danger lies in *making*, having in mind the simple nature and general form of the operating mechanism in present designs. If with such switches as those mentioned on page 462 the current had reached the maximum value of 2·55 times the breaking current, then we should have had reports of spectacular breakdowns. The present designs have stood the test of time, and I think the ratio mentioned above is nearer 1·6 than 2·55.

On page 464, under the heading "Mechanism," reference is made to the need for the mechanism to be able to close the breaker against the electromagnetic forces associated with the peak current rating of the breaker. Would the authors demand this of the mechanism in the case of a 3-phase fault when closing the circuit-breaker with high-rupturing-capacity fuses; or in a case in which the design was such that the blowing of one fuse immediately tripped the three phases of the breaker proper?

The authors do not indicate in regard to either of the designs described whether the contacts are plated in any way—either silver plating or electro-tinning.

Fig. 16 illustrates a circuit-breaker which is limited, by reason of the fuses, to a normal capacity of 400 amperes. I should be glad if the authors would state why they chose that limit and not some higher limit (e.g. 600–800 amperes) determined by the fuse ratings available.

I should welcome the views of the authors on the problem of a circuit which is being maintained on two healthy lines. This condition must occur in the case of an ordinary switch-fuse if one fuse only is blown, and motors may then continue to run single-phase until such time as the operator has appreciated what has happened. During this period there is an overload on both cables and machine.

In my view the type of gear discussed in the paper has considerable possibilities, so much so that oil circuit-breakers will probably be largely abandoned in the course of a few years. I feel, however, that it is necessary for users of low-voltage switchgear to appreciate the difficulties surrounding high breaking capacity at low voltages.

and be prepared to meet the cost, which in the past they have not been accustomed to do.

Circuit-breakers made to the authors' designs could not be sold at a low price. Perhaps the authors will express an opinion as to the value of this type of gear, in percentage terms, compared with the simple industrial circuit-breakers which have been used so much in the past.

Mr. W. A. Coates: Modern circuit-breakers incorporate little which is fundamentally novel, as designs embodying gas blasts, mechanical oil pumps, and explosion pots, have been available for over 30 years. In the last 10–15 years, research work has given us the information enabling us to design these types of breakers on scientific lines. This applies equally to the air-break development described in the present paper. The new air circuit-breaker has a performance equivalent to that of a first-class circuit-breaker in nearly every respect. The latter is sometimes quicker on make-break operation only.

Will the authors state the band of error applying to the curves in Fig. 7? This is necessary in determining the degree of possible discrimination, especially as it is stated that this breaker could discriminate with a high-rupturing-capacity fuse.

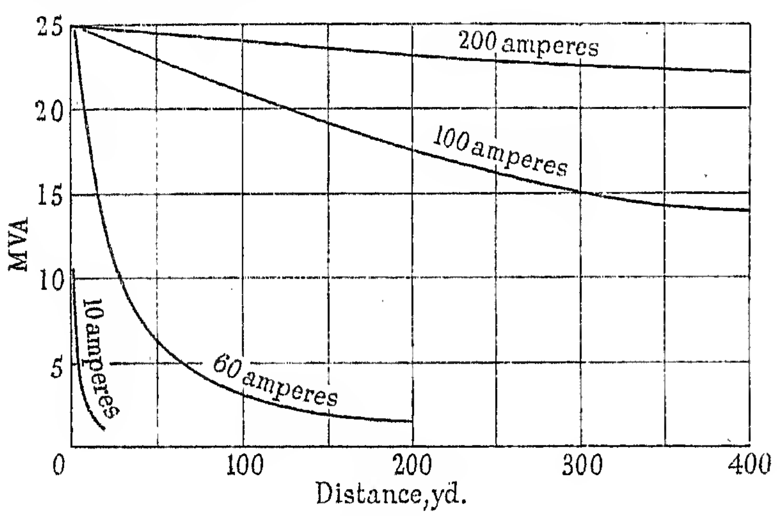


Fig. A

The analysis of requirements set out on page 463, and beneath Table 2, over-stresses the risks of high short-circuit currents associated with small breakers. The conductors to breakers in the authors' Groups 1 and 2 are effective current-limiters, as is seen from Fig. A, showing the maximum possible short-circuit MVA derived from a 1 000-kVA transformer.

I investigated the market in this country for a high-breaking-capacity small normal-current circuit-breaker a few years ago, and found it did not justify the cost of development.

As both the authors have done much to develop the technique of short-circuit testing, and contributed greatly to the production of B.S. No. 116—1937, it is suggested they should revise their paper before publication and incorporate terminology strictly in accord with standard practice.

Mr. L. Gosland: From the data in this paper, and by analogy with developments in high-voltage oil circuit-breakers over the last decade, it can be suggested that structures such as the authors describe might be capable of being developed in such a way that it would be possible to handle considerably higher voltages at the same current ratings. In any circuit-breaker in which arc extinction is aided or accelerated by control forces derived from the current interrupted, a major problem of design is that of securing a reasonably flat performance characteristic (i.e. curve connecting arc duration or arc length with current handled). In high-voltage oil circuit-breakers using arc control of the self-blast type, this problem has now been solved. Reference to Fig. 8 shows that there is still scope for considerable development in this respect in the type of structure dealt with. If, as is possible, the voltage rating of the circuit-breaker described by the authors is largely determined by its performance at currents in the region of 200–2 000 amperes, then a successful attack on the problem of removing the peak on the performance characteristic in this region might well lead to the possibility of a considerably higher voltage rating for the same structure. The increased recovery voltages should not present difficulty at the heavy-current end, since Fig. 5 shows that under these conditions the arc gap can already withstand 1 000 volts at the final arc-voltage peak; it should thus be capable of handling considerably higher peak restriking and recovery voltages.

I notice that on page 461 it is stated "... the arc on the first phase to clear can be made to extinguish at the first available current-zero, ..." although Fig. 8 shows arcing times up to 6 half-cycles. The statement might well be qualified before the paper appears in the *Journal.*

Mr. C. J. O. Garrard: The paper exemplifies how nowadays the design of almost all electrical apparatus is governed by transient conditions. Not only the apparatus but the whole layout of a system must be planned to withstand short-circuit conditions.

I do not support the statement (page 461) that the upper limit of short-circuit current in medium-voltage networks is about 44 000 symmetrical r.m.s. amperes. Where the necessary precautions have not been taken, larger currents may be encountered. Most of these difficulties are due to lack of foresight in the early stages. If one plans an installation so that it can be extended indefinitely without the short-circuit current exceeding a certain value, one generally finds after a lapse of time, when the network has grown, that one has arrived at the most economical method of dealing with the load.

The authors rightly emphasize the desirability of avoiding fire risk. There is, however, a tendency to exaggerate the fire risk due to oil circuit-breakers. I have no personal experience of an instance where the oil in a modern circuit-breaker, as distinct from that in the busbar chambers or the like, was either directly responsible for a serious fire or has been even an important contributory factor. The oil circuit-breaker is a very cheap, reliable and compact piece of apparatus, and if backed up by proper testing is not at all likely to give rise to fire. It can be housed in a smaller space than an air circuit-breaker of the same rating, because it does not emit hot gases. There are many cases, however, where the presence of oil is undesirable, and for these I have adopted the air-breaker circuit-breaker.

The authors attach importance to the desirability of making air-break circuit-breakers so that they can close and latch-in on a short-circuit equal to their maximum

rating. I cannot see why this should be necessary. Nowadays, many circuit-breakers have so-called inertia trips which are so designed that if the breaker is closed on a short-circuit it is tripped out before the contacts are fully home. Incidentally, I have found that the ordinary fuse-shunted trip coil or series overload such as is fitted to smaller breakers works quite as fast as these special arrangements. Presumably the authors' oil dashpot would not operate at so great a speed.

Reading the paper has suggested two questions to my mind: First, whether it is not time that we in this country arrived at a greater degree of standardization in regard to electrical apparatus—standardization not only of quality but also of construction and dimensions. Taking low-voltage distribution gear, for instance, there is an immense variety of sizes and designs of apparatus; one need only think of such simple things as fuses and fuse-holders, for example. The second question concerns the use of material. Should we not endeavour to use less copper, the supply of which is limited, by adopting higher voltages more freely? I think that we shall be compelled in the future to economize in the use of copper at the expense of insulating material, which either grows on trees or can be dug up in unlimited quantity.

Mr. H. Midgley (*communicated*): The paper is a welcome contribution to the available information concerning the control of medium-voltage circuits since it deals not only with a new type of air circuit-breaker designed to replace the oil circuit-breaker but also with circuit-breakers and switches of smaller current capacity, suitable for use in conjunction with high-rupturing-capacity fuses on circuits where the prospective short-circuit current may be high.

I agree with the authors in their statement on page 462 that few major interruptions of electric supply can be directly attributed to the use of oil in circuit-breakers. Nevertheless, there have been incidents in which the failure of oil circuit-breakers has been responsible for injury to personnel or damage to plant. The hazards of oil circuit-breakers are twofold: (1) the possibility of expulsion of burning oil or gases from the breaker tank; and (2) the possibility of secondary explosion due to ignition of a mixture of inflammable gases from the oil with air.

As most of the control gear for circuits of this type is directly hand-operated, any type of switchgear in which these hazards are absent will be a distinct improvement.

While the results of tests indicate that the performance of this new type of air circuit-breaker should be satisfactory, it would be interesting to know whether any of the equipments have been in service for a considerable time and, if so, what the operating experience has been.

I should like to emphasize the authors' remarks in connection with circuit-breakers and switches used in conjunction with high-rupturing-capacity fuses for circuits of small current capacity. The point regarding the making capacity and short-time rating of this apparatus is not always appreciated, and failures have occurred where unsuitable switches and circuit-breakers have been retained in use after the addition of high-rupturing-capacity fuses.

Experience has indicated that barriers between compartments of switchgear assemblies are essential if the effects of breakdown are to be limited as far as possible. Care is necessary, however, in the introduction of such barriers in the case of medium-voltage switchgear to ensure that the barriers themselves are not a cause of failure by producing flashover between phases due to a deposit of moisture or dust on the surfaces of the barriers, or, in the case of certain materials, by tracking.

I note that complete interlocks have been provided for the various equipments and, while there has been a good deal of argument about the efficacy of interlocks, there is no doubt that on medium-voltage switchgear they do tend to reduce the number of accidents of the type which arises from over-confidence of maintenance men. The temptation to rectify small defects by inserting a screw-driver or spanner into a compartment containing live medium-voltage conductors is one that some people appear to be unable to resist, and a slip of the screw-driver or spanner usually results in more or less serious burns.

In conclusion, it would not be surprising if the principle of the elimination of inflammable material in switchgear construction underlying the designs described in the paper were eventually extended to switchgear of higher voltages and higher short-circuit capacities.

[The authors' reply to this discussion will be found on page 483.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 4TH MARCH, 1940

Mr. M. N. Humphreys: With regard to the question of arc chutes, the authors state that any greater magnetic field than that prescribed unduly elongates the arc, but in connection with the device shown in Fig. 3 they explain how they have taken steps to multiply the field 5 times in order to get satisfactory operation on smaller current and have, moreover, increased the local field by making the arc horns of steel. They claim that this arrangement proves satisfactory through the range of operation, and I agree that the design seems to be such as to work very well indeed on currents from full load upwards. I think I would attach more importance than the authors appear to do, to satisfactory operation of a circuit-breaker when handling currents between full load and 10 times full load at low power-factors with the inductance on the load side of the breaker. I have known contactors which would work very nicely on full-load currents and on considerable overloads, but which would not give such satisfactory results on intermediate currents.

I should like to ask the authors why they say that the arc chute must be narrow enough to prevent the arc from zigzagging, since so long as the arc is inside an arc chute it cannot get anywhere where it is likely to do any harm. By attention to the magnetic field in which and by which an arc moves, it is possible to control an arc in such a way that it will run centrally between the walls of the arc chute without touching on either side. When magnetic blow-out without arc control is employed, the arc comes out of the shield and wanders about over a considerable distance; whilst when control of the arc is

adopted, with the same blow-out coil winding but different disposition of the pole-pieces, the arc remains much shorter and is under perfect control and quite clear of the arc shields.

Mr. W. R. Chalmers: The analysis of requirements in the paper is a valuable feature in that designers should start by stating the requirements to be met, but I do not consider the analysis to be complete or correct. I do not agree that Group 1 breakers, or contactors as they should really be called, are usually fitted with thermal overload tripping or that thermal trips are suitable for all duties. The authors specify a total life of 1 million operations for Group 1, which is probably correct as far as the mechanical duty is concerned, but when they suggest a life of 1 000 operations for the contacts, I cannot agree, as at least 100 000 operations should be expected. I should be very chary of suggesting to steelworks engineers that contactor butts should be renewed after 1 000 operations.

The breakers in Group 1 should, the authors state, be able to close on the maximum peak currents permitted by the high-rupturing-capacity fuses when closing on a 25 MVA prospective short-circuit. As to closing on a short-circuit when fuses are the protective features, they merely state (page 462) that such apparatus (H.R.C. fuses) makes no pretence at meeting any requirement of circuit-making. With small H.R.C. fuses in circuit, circuit-making is one of the easiest problems.

Regarding the limits of Group 1, it should be pointed out that motor starting-currents of 10 times full load are becoming quite common, and 14 times full load has been experienced. These figures impose very arduous conditions on thermal overloads and, where starting times of the order of 15–30 sec. are involved, this type of overload is definitely unsatisfactory.

Mr. P. J. Shipton: It is important to differentiate between circuit-breakers and contactors. The circuit-breaker is a piece of apparatus that will deal with abnormal currents and short-circuits. Now it seems to me that, referring to Groups 1 and 2, in order to obtain a circuit-breaker the authors have had to fit high-rupturing-capacity fuses, and it therefore seems to me that the better definition for apparatus in Groups 1 and 2 is contactors.

I am rather interested in the compression-type dashpot referred to in Fig. 7. Could its characteristic be altered in any way in order to obtain better discrimination between 10 and 100 sec.? Also, have any tests been carried out with that type of dashpot on frequent operation, and, if so, does it creep under such circumstances?

In connection with Group 2, which has a maximum capacity of 400 amp., I see that the authors mention thermal overloads. Are these thermal overloads indirectly or directly heated, or are they transformer-operated?

Mr. L. Breach: Any criticism I have to offer regarding the circuit-breakers dealt with in the paper, is concerned with maintenance rather than operation. On reference to Figs. 14 and 15 it will be seen that the contacts for isolation purposes are between the slab carrying the circuit-breaker and the busbar chamber, and are therefore quite inaccessible for examination unless the complete breaker is removed. As it is essential that the contacts should be frequently examined, especially so far as circuit-breakers of the higher ratings are concerned, I should like the authors to explain just what is required to make them accessible and how long the process would require. Any difficulty in connection with the equipment shown in Fig. 14 would be greatly accentuated in the Fig. 15 equipment owing to the selective action of the plug.

[The authors' reply to this discussion will be found on page 483.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 11TH MARCH, 1940

Mr. D. Adam: The circuit-breakers of the authors' Group 3 were the first oil-less circuit-breakers to be produced commercially in this country. From the illustrations in the paper it is seen that this design embodies all the best features associated with metalclad construction.

The desire to eliminate oil from switchgear is perhaps being slightly exaggerated at the moment. It must be remembered that oil is still an excellent insulating material, particularly for use at high voltages. In the present instance, however, where we have better performance as a circuit interrupter, where the best features of metalclad design have been retained, and where there is no complication arising from external pneumatic gear as in air-blast breakers, the oil-less circuit-breaker is a most logical development and to be encouraged provided that it is commercially competitive.

The breakers in Groups 1 and 2, whilst depending entirely upon high-rupturing-capacity fuses for the breaking capacity of the equipment, must nevertheless be of exceedingly robust construction if they are to withstand the through currents to which they may be subjected when closing on to short-circuit. This feature has been too frequently omitted from the fuse-switch arrangement, with the result that there has been considerable damage due to the burning-out of equipment, and generally the lighter air-break type of gear has been brought into disrepute. One has only to witness a making test with gear of an inadequate type to appreciate the damage and danger to life which may result.

What do the authors consider to be the ultimate limit in voltage for the air-break type of circuit-breaker? If the field could be extended to 6 kV or even 3 kV, and if at these voltages the short-circuit current rating was still more or less independent of voltage, this class of gear could be used for power-station auxiliaries in forming the main station boards and unit boards, as gear having a short-circuit rating of 150 MVA meets the requirements for such boards. We should then be in the position of having completely oil-less switchgear in power stations for controlling all the auxiliaries.

As most of the motors for the auxiliaries are direct-started, the air-break type of circuit-breaker has obvious advantages from the maintenance point of view when compared with the orthodox oil-immersed type. The degree of contact-burning and oil deterioration is quite considerable when oil breakers are used for frequent direct starting of induction motors.

Reference has been made in the American Press to somewhat similar types of air breakers for voltages of 15 and even 22 kV, with breaking capacities of 250 MVA. Do the authors know anything of the performance and development of these types, and can they be offered at competitive prices?

Present-day air breakers are far in advance of even the best type of contactor, and are in fact complete circuit-breakers of the arc-controlled type. From Figs. 8 and 9 it is seen that they follow the usual characteristics of arc-controlled oil-immersed circuit-breakers in that the arc-durations are short at the higher current values and longer at the smaller current values. The breaker therefore calls for a nicety in design of the arc chutes to ensure that there is sufficient magnetic blow-off at the smaller current values to make sure that the arc rises in the arcing horns and at the same time does not introduce forced current-suppression, with its resultant high rate of restriking voltage at the higher current values.

One shortcoming of the air circuit-breaker is the excessive amount of noise made when clearing under short-circuit conditions. This noise is of sufficient intensity to be quite frightening when the breakers are situated in the confines of switch chambers, and I should like to know whether it is possible for some form of noise baffle to be incorporated in the phase-barrier box, or elsewhere in the enclosure.

The authors state that the best form of contact to meet all requirements is the butt type. Would they agree that this is the only possible type so far as the air-break circuit-breaker is concerned?

It would be interesting to know whether the authors have experimented with the use of tungsten-copper, or other metals with higher melting-points than copper, for the manufacture of circuit-breaker contacts. If, say, tungsten-copper contacts were used there would be less erosion and burning of the contacts and, the amount of metal volatilized being less, some improvement in the performance might result. Further, the amount of copper and carbon dust deposited on the chutes would be less. Arising out of this latter point, do the authors consider there is any real danger, after constant operation, of this deposit forming a conducting or partially conducting path across the chutes and thereby causing restriking, or at any rate instability, of the arc? It is interesting to note from Fig. 5 that the peak-restriking voltages are reduced with increased arcing times. Have any cathode-ray oscillograms been taken under conditions of high restriking voltage, and, if so, what effect has this been found to have on the performance of the breaker?

As is to be expected with any form of air-break circuit-breaker, considerable quantities of gas are given off when currents of the order of 40 000 amperes are being broken. This gas is released by means of a spring-loaded vent. I should like to stress here the necessity for perfecting the phase barriers, as otherwise there is a great danger of the arc striking to earthed metal or even between phases. The phase barriers are subjected to considerable scorching from hot gases, and I should like to know whether any progress has been made with regard to coating them with flame-resisting paint. As these barriers are a limiting factor in regard to performance, I think they could be made even more robust with advantage. It is reassuring to note that complete barriers are fitted between each air-break circuit-breaker unit and its neighbour, to localize damage from such flashovers.

A point of considerable interest which is not brought out in the paper is the ability of the relatively small pivots in the contacts to carry large through currents for 1 sec. or even 5 sec. without burning or welding.

It will be seen from Fig. 8 that the critical arc-length occurs at current values much lower than with arc-controlled types of oil circuit-breakers. It would therefore be of interest to know what maximum arc-durations are permissible, consistent with circuit clearance.

I should like to know the difference in performance (if any) of, say, a 400-volt 25-MVA air breaker when using shunt trip and when using series trip.

In conclusion, it is reassuring to note that the authors consider that the present practical upper limit of circuit-breaker ratings generally is 2 500 MVA at 280 kV. It would, however, be more reassuring to know how it is proposed to prove this rating with the existing test plants.

Mr. J. A. Harle: It has always been realized that there were certain duties for which the air circuit-breaker was more suitable than the oil circuit-breaker, but until recently air circuit-breakers could not be used where the fault currents to be broken were large, and the oil circuit-breaker has given very good service in this field. The description of these new devices shows how the designers have taken advantage of the mobility of arcs in air to ensure that the contacts are maintained unburned and yet at the same time have avoided the production of too long arcs in air. The problem with low-voltage arcs in air is to design the breaker so that it can function in a metalclad enclosure without flashing to earth, especially after repeated operations.

As regards the screening arrangements shown in Fig. 13, I am surprised that it has not been found necessary to screen the door, as my experience with normal designs of contactors has indicated that this is usually necessary.

Have the authors met with any difficulty due to the production of nitrous fumes? These have always been a problem where repeated arcing takes place in enclosures. Has evidence of corrosion been found, and are any special precautions taken to get over the difficulty?

I am interested to know the power factor of the circuit that the authors have tested their breaker on, and also the value that they feel should be used for such tests.

The operation figures given on page 463 for the life of the various groups of circuit-breakers appear to be very large, and further information on the basis on which these have been selected would be of value. For Group 1 a life of 1 million operations is suggested: assuming a life of 20 years, each year consisting of 300 working days, and 8 hours' work per day, gives 20 operations per hour or 1 every 3 minutes. Considering Group 2 breakers also, if these are required to remain closed for periods ranging from half a day to a week, it is difficult to understand why their life should be assessed at 100 000 operations. Further, a definition of "total life" is required, as I anticipate that this term does not mean the life of one set of contacts.

One of the disadvantages of air-break circuit-breakers has been the voltage rise which they produce on the system. In the paper an example is given for 27 000

amperes breaking current and a recovery voltage of 380 volts, and the voltage rise under this condition does not appear to be excessive. It would be interesting to know the corresponding figures for 33 000 amperes and a recovery voltage of 440 volts, particularly as from Fig. 8 it appears that at currents of this order the arcing time in many instances is less than 1 half-cycle.

I note with interest the authors' scheme (Fig. 16) for combining the high-duty cartridge fuse with the discriminative contactor, as this approach is one which I think will be more extensively employed in the future. Naturally it must be used with caution when one approaches the maximum size of air-break circuit-breaker that can be employed with the fuse ratings available, but even then the scope of the combination gives a broad range of economical switching arrangements.

As regards the 10-ampere high-rupturing-capacity fuse shown in Fig. 11, I should appreciate the authors' confirmation that open-wire fuses in insulated carriers up to 10-ampere rating are satisfactory for prospective short-circuit currents of the order of 33 000 amperes, especially as most manufacturers have produced cartridge fuse-links for use at current ratings as low as 5 amperes.

It is appreciated that if an open-wire fuse has been developed for 10 amperes and category of duty 440AC4 such a fuse will be invaluable to supply authorities where the fault values on the network are high but individual services require a small current rating.

Mr. E. C. I. Macdonald: While I agree with the authors' conclusions regarding the limit of the short-circuit powers encountered in medium-voltage networks, in my experience fault powers as high as 50 MVA are exceptional on supply networks as generally understood, and 50 MVA is not common even on large concentrated industrial power supplies at medium voltages, at any rate in this area.

The authors stress the fact that circuit-breakers and their ancillary equipment must withstand without damage both the magnetic and the thermal effects of the current impulse permitted by the largest size of high-rupturing-capacity fuse with which they will be used. I am sorry to observe, however, that they do not stress this point in respect of the apparatus in which high-rupturing-capacity fuses themselves are carried. There is no doubt that modern high-rupturing-capacity fuses are fully capable of doing all that their makers claim, but the buyer, and too often the supplier, frequently appears to ignore the necessity for ensuring that the mounting and housing of the fuses and busbar fixings are adequate for use in circumstances where the fuse itself may be entirely suitable. It is only necessary to refer to the penultimate paragraph of the authors' Introduction to see the importance of the mechanical strength of low-voltage equipment.

Another point of design which appears to be part of the never-ending battle between adequate engineering design and economics is the tendency to introduce fuses of heavy current rating into enclosures which were not designed for such large fuses. The necessary increase in the cross-section of conducting parts often results in severe reduction in clearances, which brings in its train excessive heating and additional risk of breakdown due to dirt accumulating in inaccessible spaces between live parts. Manufacturers should watch this question of clearances, not so much from the strictly electrical point of view as from the practical aspect of access and maintenance.

Mr. A. T. Robertson: It is unfortunate that the breaker arrangement shown in Fig. 13 is such that a back access passage is necessary, because this feature makes lining-up inconvenient with the switch-fuse gear shown in Fig. 16 (Plate 2), which is essentially of the wall-mounting type. Oil breakers for a similar duty would have busbars, etc., accessible from the front, and so would line up naturally with the busbars of the switch-fuse gear.

The authors indicate that with a properly designed arc chute there is no difficulty in controlling medium-voltage arcs, and it is true that even the heaviest-current arcs can be extinguished within the arc chute. When air breakers with such chutes are enclosed the problem is, therefore, to cool the metal vapour and gases in as small a space as can be made convenient, and this would seem to be done most efficiently by forcing the gases into intimate contact with large surfaces of metal. I should like to know whether the authors have considered employing some such arrangement in substitution for the arc barriers, or in conjunction with them, as a means of reducing the size of the enclosure.

The authors' statement that the main contacts have to carry the peak rating until the breaker is tripped and until the current is transferred to the arcing contacts, would seem to indicate that the arcing contacts do not share the load current when the breaker is closed. I should like to know whether this is the meaning intended. Could a breaker with, say, ten 200-ampere main and ten 200-ampere arcing contacts be rated at 4 000 amperes normal load, or would it be necessary to provide the full 4 000 amperes carrying capacity on the main contacts with, say, four 25 000-ampere peak-current arcing contacts in addition?

In explaining that the ordinary switch-fuse is inadequate for many circuits the authors give the inching current of direct-starting induction motors as 10 × full-load current. This is about the right value for the current on first switching on, but the value may be more than twice this, i.e. 20 × full load, when inching if the circuit is reclosed before the motor flux has died down, and this may take a second or so.

[The authors' reply to this discussion will be found on page 483.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 16TH APRIL, 1940

Mr. H. Pearce: Importance is attached to the fact that the breaking capacity of a medium-voltage circuit-breaker is essentially a function of current and not of voltage. I should have felt happier if still greater emphasis had been laid on breaking current rather than on MVA. The latter is perhaps convenient for high-voltage breakers, but for medium voltages it is misleading. The performance of any circuit-breaker merely justifies a rating of so many amperes at so many volts, and I hope the forthcoming British Standard for medium-voltage circuit-breakers will take full account of this.

The authors have been a little too generous in taking

2·55 times the rated rupturing-capacity current for their peak value of making current. It is true that this is the figure accepted as appropriate to high-voltage circuits, but for medium-voltage circuits the peak current does not in general reach so high a figure. The Tables in the paper show that even after 3 or 4 half-cycles (i.e. the total break time) there is no difference between asymmetrical and symmetrical current. The reason for this is the higher proportion of resistances in a medium-voltage circuit. If the breakers had been tested in their normal position instead of quite close to a test transformer, that effect would have been even more marked. A factor of 2 would be very much nearer the actual conditions on a medium-voltage system than 2·55.

The authors are a little obscure in their treatment of the relative difficulty of d.c. and a.c. making currents. The words they use seem to imply that alternating current is more difficult to make because the peak current is $2\frac{1}{2}$ times the rated breaking current (that is, adopting their ratio of $2\frac{1}{2}$). In point of fact, however, to make a peak current of so many d.c. amperes is no easier than to make an alternating current.

The authors recommend not only that the breaker should be able to make a circuit carrying a peak current of 2·55 times the rated rupturing-capacity current, but also that the breaker should be able to latch against such a current. If I had two circuit-breakers offered to me, one of which would latch when closed on a short-circuit and another which would open instantaneously, however hard I tried to close it, I should choose the latter. I do not think the supply industry wants a circuit-breaker to close on a short-circuit; in fact, the sooner the short-circuit current is interrupted the better.

On page 467 it is stated: "Breakers fitted with such dashpots can be made to discriminate one against another, and against any high-rupturing-capacity fuses which may be installed in series." I take it that the authors do not mean that the breaker will always open before the fuse clears.

Mr. S. R. Mellonie: This paper deals with an interesting and important development which is, however, scarcely new. There were air circuit-breakers in operation at least 12 years ago on voltages as high as 13 000 volts: I refer to the original de-ion breakers.

The authors do not mention that air circuit-breakers are noisy. Are there any means of causing them to operate quietly?

Have these breakers shown any tendency to limit a prospective short-circuit current by reason of their speed of operation? I understand that certain low-voltage oil circuit-breakers have shown such a tendency. Can the authors confirm this, and can they offer any explanation of the difference between the performance of the two types of breakers?

Turning to the details of the paper, it should be noted that the only true circuit-breakers are those in Group 3. The devices in Groups 1 and 2 are circuit-makers, the fuse being relied upon to break the circuit. One must bear in mind, therefore, that the applications of Groups 1 and 2 bring with them all the difficulties possible with single-phasing unless some device for dealing with this is incorporated as part of the breaker.

The authors' work on chute design recalls a case I came across some years ago where the arc of an air circuit-breaker, instead of following the arc chute, went down the panel as far as the floor (the meter being mounted near the floor). The trouble was due to the way in which the leads were taken to the particular breaker.

I am disappointed to see in Fig. 11 (Plate 2) a rewireable high-rupturing-capacity fuse. For many years manufacturers and certain enlightened undertakers have followed a course which has resulted in the adoption of cartridge fuses in 99 % of cases. It is, I suggest, a retrograde step to re-introduce a type of fuse which is open to much misuse.

I am not in favour of cubicle-gear interlocks. It is better to spend the extra outlay, which these represent, on securing a competent staff to carry out the maintenance work.

Mr. G. F. Sills: Many people are beginning to realize the advantages of the low-voltage air circuit-breaker of the type which has passed definite rupturing-capacity tests in a modern switchgear-testing station. It would not be right to say, however, that this new-type breaker should take precedence over the oil circuit-breaker for all purposes, as there are certain types of chemical works where the oil circuit-breaker with proved rupturing capacity is to be preferred.

Modern circuit-breakers of the type shown in Fig. 13 will stand a through short-circuit lasting 5 sec., but when such a breaker is combined with various other pieces of apparatus such as low-capacity current transformers it is not certain that the whole piece of apparatus will stand this period of short-circuit.

I would make a plea for more serious consideration of the type of l.v. switchgear advocated by the authors, particularly for all important installations. A modern power station with two 30 000-kW sets costs, say, £1 million, and since such a large amount of money is involved it does not seem reasonable that the low-voltage switchgear controlling the auxiliaries should be of the oil-immersed type with the attendant risks of fire and explosion. Tremendous strides have been made in the construction of large air-blast-type switchgear, and the question of possible fire risks from oil in modern turbine plant is being tackled very seriously, not only in connection with electrical gear but also in connection with the material and positioning of the turbine oil pipes.

Many of the low-voltage oil switches controlling important auxiliaries in power stations have very little rupturing capacity, and if they were called upon to deal with a severe short-circuit would be capable of causing a shutdown through starting a fire, apart from doing other damage. The modern low-voltage air breaker may cost more than an oil switch, but if two or three rows of ornamental bricks were replaced by plain bricks in the construction of the power station it might more than pay for the increased cost of the low-voltage air-break switchgear. I have knowledge of somewhat similar gear to that shown by the authors which has been developed and tested up to 100 MVA at 3 kV.

As the authors state, the new type of air-break switchgear is most useful in heavy rolling-mill work. I saw a recent application in a large mill of this type, which had cost £3 millions, where each of the main motors had its

main control low-voltage air-break switch panels placed immediately under it in a long basement, the busbars being supported from the walls. This seemed to be a preferable arrangement to having the panels all made up as one board, with the usual cable-runs.

Mr. H. G. Bell: In referring to the smaller switches on page 463, the authors state that an under-voltage release feature is nearly always required. Experience has shown that no-volt release relays without time-lags have been the source of an incredible amount of trouble, particularly on large systems. In many cases instantaneous drops of voltage cause unnecessary operation of these no-volt relays, with consequent unnecessary loss of load.

To the general principles of switchgear design mentioned on page 471 I consider that "accessibility" should be added.

Fig. 14 shows the control fuses as being mounted in a box which is not at all easily accessible. Moreover, the terminal board shown in the same Figure is mounted laterally, a fact which detracts seriously from its accessibility. Terminal boards should preferably be so mounted that they can be clearly seen by an operator with his head outside the cubicle.

The system of busbar insulation adopted by the authors is a very good feature that might be extended to various busbars in control and relay panels associated with other types of switchgear.

Mr. R. W. Todd: The authors can claim to have proved that electrical engineers are victims of fashion just like other human beings. The first circuit-breaker that was ever used was an air circuit-breaker. Later the oil circuit-breaker was introduced, and used for both high and low a.c. voltages. Then the Germans made a large number of very bad oil circuit-breakers which caused many fires. Because of this Germany had to resort to air circuit-breakers for even the higher voltages. Now the tendency is for even low-voltage breakers to be of the air-break type.

On page 462 the authors admit that oil circuit-breakers have done very good work, but they point out three failings. The first is "Relatively severe contact-burning with frequent switching at currents of the order of normal up to 10 times full load." I should like to know what is meant by "relatively severe contact-burning" and "frequent" operation. In general, low-voltage circuit-breakers operate only 3 or 4 times a day at the most, and the oil circuit-breaker has proved quite capable of doing that.

The authors' second criticism of the oil circuit-breaker concerns its "Relatively long total-break time." To show that this is not a fair criticism I have compared a few of the test-results given in Table 2 with some others obtained on a commercial oil circuit-breaker. For Item 3*c* of the Table the short-circuit currents are given as between 36 000 and 40 000 amp. with an arcing time of 0·8 to 0·92 half-cycle. The oil circuit-breaker on the same current gives an arcing time of less than 0·5 half-cycle and a duration of short-circuit of 2 cycles. The authors do not state the duration of short-circuit in their tests, and I should be glad to know whether they have any information on this subject. In Item 4*a*, a short-circuit current from 19 000 to 20 000 amp. is given with an arcing time of from 1·1 to 1·4 half-cycles. The oil circuit-breaker mentioned above gave an arcing time of less than 0·5 half-cycle and a total time of 1·9 half-cycles on the same current. Finally, Item 7*c* with a current of 3 300–3 400 amp. shows an arcing time of 1·4 to 1·5 half-cycles. The oil circuit-breaker gave an arcing time of 0·69 to 1·2 half-cycles with a total time of 4·7 half-cycles. These figures show that this oil circuit-breaker is faster than the air circuit-breaker mentioned in the paper.

I am interested to note that the designer of the contact arrangement shown in Fig. 1 has entirely dispensed with shunts, which have caused much trouble in the past.

On page 471 it is stated that the width of the arc chute should be the diameter of the arc. Can the authors give any further information on this matter?

Mr. W. D. Sutcliffe: I should like to deal chiefly with the temperature rise of switchgear such as is described in the paper.

Temperature-rise considerations cause far more trouble and failures than any question of rupturing capacity. In my experience industrial air-break switches of ratings up to 500 amp. have had to be removed from service because they have given trouble due to excessive temperature, but none have had to be removed because they failed to rupture a fault. Switches which incorporate high-rupturing-capacity fuses also cause trouble because a higher temperature-rise is produced than exists in the absence of fuses. We badly need a British Standard covering a combined switch and fuse, because very few switches which are on industrial loads, particularly above 300 amp., will comply with the appropriate British Standard for switches if they have fuses incorporated. We find fuses mounted on the moving part of the switch, a practice that is to be deprecated for many reasons; one being the temperature rise, and another the danger that when a man tries to remove or replace one of the fuses it is quite easy for him to touch a live contact on this type of switch. The fuses ought to be fitted in a separate chamber. A short time ago when we wanted a switch to deal with a 300-amp. 400-volt industrial load of 10 hours' duration we were advised by the manufacturer to use a 400-amp. switch incorporating a 300-amp. fuse, presumably on account of temperature-rise considerations.

We have tested many fuse barriers on industrial switches, and we find that 75 % are made of tracking material; this is a very big fault because, in the event of arcing taking place, the switch blows up, since the barriers became conductors.

Mr. J. A. Henley: It is a pity that the authors did not allow themselves space to describe arcing phenomena associated with the oil-less breaker. In particular, more comment might have been made on the interesting cathode-ray oscillogram of Fig. 5, which would have been more instructive if it had been accompanied by the corresponding Duddell oscillogram.

Interruption in the authors' breaker—judging by the cathode-ray oscillogram—is of the type which has been called "d.c. interruption." Extinction of the arc does not depend entirely upon the fact that the current naturally passes through zero. The arc is lengthened and cooled until its resistance becomes the predominating factor in controlling the short-circuit current, which is reduced in magnitude while the power factor increases to something approaching unity.

As shown by Fig. 5, the current is forced down to zero near voltage zero with such rapidity that a surge is produced, but this is damped to harmless proportions by the residual leakage in the arc path.

It would appear that breakers which interrupt on this principle are definitely limited in regard to the voltage for which they can be designed while still retaining a size which is suitable for use in a metalclad unit. This is because interruption depends upon lengthening the arc, so that the necessary arc-length increases with voltage, the size of arc chute increasing accordingly.

Oil-less breakers have already been produced with a breaking capacity of 150 MVA at 5 kV in which interruption is by magnetic blow-out and a refractory arc chute without the assistance of an air blast. Judging from the size of arc chute necessary for this rating, I should think it unlikely that breakers of the general type of the authors' breaker will be produced for voltages of the order of 11 kV.

Mr. W. H. Lawes: It is not clear that the air circuit-breaker is a better piece of equipment than the oil breaker. Some 35 years ago the late Mr. W. Duddell found that the oil breaker broke current very certainly at voltage-zero, and he even went so far as to recommend a special resin oil for use in such breakers.

As regards discriminative protection, I would remind the authors that oil dashpots are not oil-less, and that therefore they do not come within the scope of the paper. The "definite minimum time" of an oil dashpot is liable to become indefinitely long in the winter, and in the summer indefinitely short. Clockwork mechanisms operating a fan are much more reliable in this regard.

Mr. J. M. Gillespie: One aspect of the subject which is not covered by the paper is the range of application of air-break switches. The illustrations in the paper suggest that the bulk of these switches is such as to limit the field of application even in circumstances where the absence of oil would be particularly valuable, as, for example, in underground equipment. Here air-break contactors are already used for coal-face switches, but oil circuit-breakers are still used for feeder switches. The question of bulk is particularly obvious in the case of line switches for direct-started 2-speed induction motors such as are used for driving power-station auxiliaries. I believe that the authors have designed equipment for this service in which two switches are mounted side by side with a timing-relay panel. The whole assembly would appear to take up treble the floor space required by a contactor equipment.

It would be valuable if the authors could indicate the relative price and floor space taken up by the three alternatives—oil circuit-breakers, air circuit-breakers, and the very useful combination of air-break contactors and high-rupturing-capacity fuses.

Mr. W. E. Swale: The attractions of oil-less switchgear for use on consumers' installations are obvious, particularly when it appears that gear of this type, when made up into switch panels, will occupy less room than an equivalent oil circuit-breaker equipment.

In none of the authors' illustrations is there any indication of the presence of instruments. One would like to have an assurance that so far as oil-less switchgear is concerned the fitting of the usual instruments, i.e. ammeters and/or watt-hour meters, offers no difficulties.

Mr. G. H. Sammons: The peculiar isolation arrangements of this type of switchgear have driven the designer, no doubt unwillingly, to employ Bowden wire for switch operation. This is a very unsatisfactory arrangement, and I am of the opinion that a Bowden wire will not give satisfaction over a period of 20 years, which may be taken as the usual life of such apparatus.

With regard to the method of isolation, it appears to me preferable to fit shutters over the live contacts of the busbars, in order that the isolation shall be quite positive.

Mr. W. N. Y. King: In my view the air break requires more space than the oil break in which to dissipate the energy of the arc. Therefore, if an air-break switch is installed it will require more room above it to break the arc, and there will be a danger zone which should be allowed for. This point would not be important in a large power house, but in a smaller building there might be some object overhead which would get damaged by the arcing of the air-break switch.

Mr. W. Kidd: I have seen some of these oil-less switchgear equipments in manufacturers' works, and would suggest that an effort should be made to improve their external appearance.

The authors state that they provide openings in the top and bottom of the 3 000-amp. panels to allow for ventilation; now this type of switchgear is not usually installed in dustless rooms, and I should therefore expect a good deal of dust to get into the cubicles, even if they have wire gauze over the openings.

The mechanical forces set up in switchgear during fault periods are much higher than is generally realized, and therefore users and contractors should ascertain from the supply authority what kVA capacity of circuit-breakers should be installed. I am pleased to say that we are getting co-operation between the parties concerned in Manchester, but there are still many danger spots; only a few days ago I was notified of a 6 000-kVA breaker in a position where it had to deal with 14 000 kVA. Of course, it failed when trouble occurred.

[The authors' reply to this discussion will be found on page 483.]

EAST MIDLAND SUB-CENTRE, AT NOTTINGHAM, 23RD APRIL, 1940

Mr. B. C. Bayley: The paper must cause some disquiet amongst those engineers who are responsible for a.c. plant, subject to heavy short-circuit currents, that is not equipped with modern air-break pattern control and protective gear. The authors lay particular stress on the importance of having suitable gear that will "make" the circuit under these severe conditions, and draw a vivid picture of the difference in requirements of gear dealing with direct-current as distinct from alternating-current circuits. Since the introduction of the grid system the currents in l.v. systems have increased enormously, and considerable risks are now being run by retaining old equipment which is quite unable to handle this hazard.

The authors would have us believe that the modern air circuit-breaker of the contactor type, and the non-

automatic circuit-breaker in series with high-rupturing-capacity (H.R.C.) fuses, meet all the conditions that are likely to be found on modern layouts limited to 25 MVA —and there should be no difficulty in designing a layout within this limit. There are, however, some difficulties in obtaining discrimination between successive fuses of the H.R.C. cartridge type, and a more reliable performance might be obtained if fuses of the same make and characteristics were utilized.

There are many applications where the H.R.C. switch-fuse combination has overlapped the functions of the oil circuit-breaker, but except in the larger sizes this combination shows no saving in cost over oil circuit-breakers. Although the cartridge high-duty type fuse, if properly designed, is capable of rupturing large currents suddenly without appreciable voltage-rise, I am still of the opinion that for overload protection the semi-enclosed re-wirable fuse, backed up by a H.R.C. fuse, is the best arrangement.

Referring to Fig. 16 (Plate 2), I notice that the spiral spring controlling the operating-handle shaft is not shielded or trapped in any way, and since these springs are liable to break I consider steps should be taken to avoid the risk of earthing one phase, an operation which is likely to result in severe damage to the equipment.

The authors showed in one of their slides a group of switch-fuses and one incoming air circuit-breaker mounted in the form of a switchboard. This assembly appears to me to lack rigidity, and in the case of the larger current-carrying units I consider there is a risk, where armoured cables are used, of damage being caused to the cable joints.

Mr. B. Nuttall: I am very interested in this paper, chiefly from the point of view that an endeavour has been made to supersede the oil circuit-breaker for medium-voltage duty; but I am unconvinced that this purpose has been wholly achieved.

The larger the current-carrying capacity the more difficult the problem of ventilation becomes. For capacities of 3 000 amperes and upwards in steel enclosures, it is essential to create a steady draught through the cubicle and to ensure that the air is "clean." The ventilators would also have to be made still larger to allow for the area occupied by verminproof gauze. This would seem to indicate that filtered air is essential for this gear in cement and flour mills, quarries and other onerous conditions of operation, for air is a very unstable dielectric when polluted. Have the authors carried out any experiments to simulate such conditions? If so, is the performance of the breaker altered in any way when making or breaking its full short-circuit rating? Under such conditions the oil circuit-breaker would be preferable and, incidentally, cheaper both in first cost and as regards maintenance.

Until more experience with the air-break circuit-breaker is acquired, I suggest that its application is more suitable for the control of power-station auxiliaries where the elimination of oil justifies the expense of the precautionary measures outlined above.

In the equipment shown in Fig. 14 the isolating plugs and sockets appear to be very difficult to examine or overhaul. This is essential after the gear has cleared a short-circuit, and is advisable, say, every 12 months for maintenance purposes.

Lastly, have the authors carried out short-circuit tests on a complete switching equipment, i.e. including isolating features and current transformers?

THE AUTHORS' REPLY TO THE DISCUSSIONS

Messrs. H. E. Cox and **L. Drucquer** (*in reply*): We have much appreciated the discussion as it has directed our attention to many possibilities of improvement and extension of the line of switchgear covered by the paper.

In the following reply we have attempted to deal with the many points of general interest raised, and we wish to apologize for any omissions to deal with specific points of detailed interest only.

For easy reference the replies have been collated under specific headings.

Enclosure

Whilst we agree with Mr. Knowles in his view that heavy-current equipments having an interrupting capacity of 50-MVA are undesirable, we consider, nevertheless, that certain existing installation problems can only be solved economically by the use of such equipments.

Some attention has been focused on the question of fitting silencing baffles, but within our experience the noise under full fault operation, using air in its free state and with the breaker totally enclosed, is not sufficient to warrant the additional complication of baffles.

It has not been found necessary to provide insulation screens on the inside of the door, it having been proved that earthed metal can be brought to within a distance of 4 in. of the arc chute opening, without causing failure to earth.

Interlocks

We are unable to agree with Mr. Mellonie's suggestion that interlocks are unnecessary and we strongly support Mr. Midgley's contention that such features should form an integral part of the design and thus conform to the high level of safety in operation which characterizes British metalclad switchgear.

Arrangements of Gear

In reply to Mr. Leach, the switchboard shown in Fig. 16 can be arranged with the fuses adjacent to the busbar, or, alternatively, additional isolation can be provided between the switch and the busbars. Accommodation for a full complement of instruments and meters can be arranged. Shutters can be provided for the busbar plugging contacts illustrated in Fig. 14.

Ability to Handle Through Fault Current

We agree with Mr. Knowles that the short-circuit should be maintained for as short a period as is appropriate to its position in the system. On extensive systems, however, to obtain discriminative protection, it is necessary to keep the main breakers closed for considerable periods, and 5 seconds would not appear to be an excessive upper limit.

Extensive tests have proved the ability of the pivot

pins to carry the full short-circuit current for 5 seconds as mentioned by Mr. Adam.

Mr. Knowles is correct in his assumption that the braids shown in Fig. 3 have to withstand momentarily (for only a portion of the arcing time) the full short-circuit forces, and the construction has proved adequate.

Reduction of MVA due to Cable Connections

We agree with Messrs. Leach and Coates that small cable connections reduce the short-circuit current, provided the location of the fault is such as to include the reactance of the cable.

Methods of Protection

In reply to Mr. Knowles we would advocate instantaneous trips for any ampere and MVA rating of circuit-breaker, provided the requirements of discriminative protection are met.

Our preference is for an indirectly-heated current-transformer-operated thermal overload for 400 amperes and above.

In reply to Mr. Garrard, we view inertia trips as a complication, and tests have shown them to be unnecessary with the type of breaker described in the paper. It is believed that both Messrs. Garrard and Pearce will agree that a circuit-breaker of economical design, capable of closing on to its rated short-circuit current, is superior to one which requires the addition of an inertia trip.

Operation and Performance

In reply to both Messrs. Lythall and Pearce, in our experience, whilst it is unusual, it is possible for the peak making current to be as high as 2·55 times the r.m.s. symmetrical breaking current, and a gear for universal application must take cognisance of this.

When a breaker is used in conjunction with H.R.C. fuses, the mechanism need only be designed to close the breaker against the peak current permitted by the largest size of fuse with which it is designed to be used.

In reply to Mr. Humphreys, zigzagging of the arc increases the arc energy by lengthening the arc without a corresponding current-suppression effect, unless the separate elements forming the zigzag are prevented from short-circuiting. The interleaved chute used in the Magne-Blast breaker is a construction which achieves this.

We can assure Mr. Mellonie that there is no danger of the chute being covered by harmful copper deposits, provided the short-circuit current does not cause "spluttering" of the contacts prior to parting.

Such "spluttering," when it occurs, is responsible for the short-circuit current-limiting tendency which is shown by some oil circuit-breakers and which is entirely absent in the type of circuit-breaker covered by the paper.

Mechanical Construction

Several speakers referred to details of mechanical construction.

It has been found preferable to obtain correct toggle positioning by accurate jigging, rather than by individual adjustment which can be interfered with.

In general, we agree with the contention that spring isolation contacts should be on the moving portion, but certain peculiarities of the design adopted made the arrangement shown the most economical.

The breakers referred to on page 467 utilize pressure line contacts, and we agree with Mr. Adam that such butt contacts are the only economical solution.

We have found the use of the relatively expensive tungsten alloys for contacts to be unnecessary.

The arc chute acts as a gas cooler and occupies no greater space than any other practicable form of cooler.

Single-Phasing

Reference has been made to motors running under single-phase conditions in the event of one fuse blowing, and devices which would prevent such an occurrence would appear to have technical merit. The sphere of application of such devices is, however, not immediately apparent unless they can be provided at negligible cost.

Voltage Limits

Several speakers referred to developments for voltages higher than 660, 3-phase. Such developments, whilst possible, do not come within the scope of the paper.

Barriers

References to the value of phase barriers were made by several speakers and certain criticisms were levelled at the type described.

The barriers finally chosen were developed from results obtained on the short-circuit test plant, on breakers totally enclosed in metal housing and, although we do not claim them to be the only or most efficient type possible we can assure Messrs. Midgley and Knowles that they are effective.

Accessibility

The question of accessibility has been considered in the design of the complete switchgear.

The breaker contacts, which require most maintenance, are readily accessible and removable.

The plugging contacts of the arrangements shown in Fig. 14, which are less accessible, are silver-plated and of the pressure line multi-finger construction. A lifting device is available for removing the complete moving portion from the cubicle.

Corrections to Paper

We wish to thank Mr. Coates for his criticism regarding terminology used in the paper; these errors have been corrected for the *Journal.*

We also wish to thank Mr. Gosland for pointing out an ambiguity regarding arcing times under the heading "Short-circuit rating." We hope that the meaning has been changed by the correction which has now been made.

MAINTENANCE OF RELAYS AND ASSOCIATED EQUIPMENT

By J. R. BROOKMAN, M.E., Member.*

(*Paper received* 16*th February*, 1939; *read before the* METER AND INSTRUMENT SECTION 2*nd February, and before the* NORTH-WESTERN CENTRE 23*rd January*, 1940.)

SUMMARY

The author gives a brief description of a transmission and distribution system in South Australia and the protective relays used in connection therewith. Maintenance methods are described and operating results tabulated and analysed. The operating results reveal a protective efficiency of over 90 %.

INTRODUCTION

The art of eliminating faulty electrical circuits from an electrical system without disturbing the sound ones, has made great strides during the past 10 years, and protection engineers are now able to provide satisfactory solutions for many problems that would have baffled them a few years ago. It is therefore rather disappointing to find that such poor results are obtained as those shown in Table 1. These have been calculated from data given in Tables 2, 5, 11 and 12 of E.R.A. Report F/T94,† on the same basis as that adopted in Table 5 (see page 493). The performance attained in busbar protection is the only one which can be classed as reasonably good, whilst in generator protection it is deplorable. From a study of the report it would appear that inadequate maintenance of the protective devices is largely responsible for the unsatisfactory results.

Table 1

ANALYSIS OF RELAY OPERATIONS

Plant protected	Number of operations	Percentage of operations correct	
		Author's formula	E.R.A. Report formula
Generators ..	48	56·5	87·5
Transformers ..	395	68·5	97
Busbars	82	90	100
Feeders	4 538	86·5	98

An account of the protection maintenance methods which have been successfully used in a comparatively small undertaking which has, nevertheless, a large mileage of 33-kV transmission lines and 7·6-kV feeders, may be of some assistance to engineers who are experiencing difficulty with their protection.

DETAILS OF PROTECTIVE SYSTEM OF ADELAIDE SUPPLY UNDERTAKING

The transmission and distribution lines of the Adelaide Electric Supply Co. extend about 200 miles north and south and about 40 miles east and west in the more thickly populated part of the State of South Australia. The number of consumers supplied is close to 100 000, of whom 90 % are in the metropolitan district of Adelaide.

A single power house at Osborne, near the mouth of the Port River, supplies the system through four double-circuit 33-kV transmission lines, having an average length of 12 miles. These lines terminate in three major substations which are connected to other city and suburban substations by 33-kV ring mains. At the substations, step-down transformers reduce the voltage to 7·6 kV to supply distribution transformers in the surrounding districts. In the more densely loaded city areas, the voltage is stepped directly from 33 kV to 415/240 volts. The 7 600-volt feeders are usually radial, but a few operate as tie circuits between substations. A number of 7·6-kV feeders have reclosing circuit-breakers, and the remainder are now being fitted with reclosing gear.

There are 453 circuit miles of 33-kV overhead line, 421 miles of 7-kV overhead lines, 7½ miles of 33-kV underground cable and approximately 15 miles of 7-kV cable. There are three 33-kV substations with indoor ironclad gear, the rest being outdoor-type stations.

On the 33-kV lines some trouble is experienced with large birds, necessitating bird guards on steel cross-arms, and the use of tall insulator pins. Other birds have the quaint habit of building their nests on transmission-line poles with fencing wire or any other wire they can get hold of, and they occasionally short-circuit the 33-kV lines. A further trouble is occasioned by saline dust accumulating on the insulators, so that regular cleaning is necessary. The 7-kV lines suffer in stormy weather from twigs or branches blown from trees, and, to a considerable extent also, from stray motor vehicles colliding with the poles (there is one motor vehicle for every 6·5 persons in South Australia). On the other hand, lightning is not severe, and there is no trouble from sleet. The types of protection in use on various circuits are indicated in Table 2.

All pilot-wire relays and balanced circuit relays are instantaneous in action. The use of graded time-delays is avoided wherever possible, except as back-up protection. Both British and American relays are used, and telephone-type relays are employed in connection with some of the pilot-wire schemes, and for the indicating circuits. In selecting relays with inverse time characteristics, care is exercised to ensure that their time/current curves do not "cross" those of other similar relays with which they may be associated in adjoining sections of the system. Purchases have, in fact, been limited to three or four makes, the characteristics of which are very similar. Before being placed in service each relay is thoroughly

* Adelaide Electric Supply Company, Ltd.
† *Journal I.E.E.*, 1936, 97, p. 541.

Table 2

Circuit	Type of protection
Double-circuit 33-kV transmission lines	Operated as balanced pairs with instantaneous selective biased relays tripped by current unbalance
Double-circuit ring main, 33 kV	Operated as balanced pairs with instantaneous non-selective, non-biased relays tripped by current unbalance
Short single-circuit 33-kV tie lines between substations	Several modern types of pilot-wire protection are used
Long single-circuit 33-kV transmission lines supplying country districts	Graded time overload relays on radial lines, directional overload relays on ring or tie circuits
Underground 33-kV cables	Pilot-wire type on tie circuits. Instantaneous fault and overload time-delay type on radial circuits
7·6-kV lines and cables	Directional overload relays on tie circuits. Fuse-shunted trip coils on radial feeders
33-kV and 7·6-kV busbar zones*	Frames insulated from earth and connected to earth plate through current transformers operating multi-contact relays
Transformers	Howard leakage protection and Buchholz relays
Generators and their transformers	Generators are connected to 33-kV busbar through step-up transformers. The generator and associated transformer are protected as one unit by the Merz–Price balanced-current system using biased relays

* See author's discussion on paper by Mr. F. C. Winfield (*Journal I.E.E.*, 1937, **81**, p. 717).

cleaned and examined on the test bench. Inverse time-limit relays are checked and adjusted so that their actual characteristic curves are very close to a common standard for that type rather than to the maker's curve for the particular relay.

All test data are recorded by the tester on forms which are pasted into registers having a page for each relay. The installation, removal, or alteration in setting of a relay, is also recorded in this way, so that the whole history of any relay can be readily seen on a single page of the register. Figs. 1, 2 and 3 are samples of the record slips used.

The relays are mounted on steel, or slate, or insulating composition panels. The panel wiring is cambric-insulated braided flame-proof wire, clipped neatly to the back of the boards. Lead-covered multi-core vulcanized-rubber cables are used between the relay panels and the switchgear. The minimum size of panel wire used is 1/14 S.W.G. Metal clips or thimbles are used for attaching wires to the instrument stems. Test links in current-transformer circuits are avoided. All wires are tagged at their ends, in accordance with the letters or numbers of the wiring diagram. The batteries employed for closing and tripping purposes each consist of eighteen 6-volt, 115-ampere-hour, motor-car type accumulators, which are trickle-charged. Formerly, 30-volt alkaline batteries were used with success, until solenoid-operated breakers requiring comparatively heavy currents were introduced. Alkaline batteries are still used for tripping duty, but only in country substations with infrequent attendance. They retain their charge satisfactorily for a period of 6 months without trickle-charging. They are completely overhauled every 3 years. In addition to the bench test previously mentioned, relays are tested after installation by passing current through the primaries of

Adelaide Electric Supply Co., Ltd.
Substation Dept.

Relay Register Slip

RELAY NO.................MAKE...............TYPE...............

FIXED AT...................SUBSTATION...................

REMOVED FROM

LINE..............CIRCUIT..............PHASE NO..............

LEVER SETTING.........CURRENT TAP.........PLUNGER SETTING.........

REMARKS.................ATTENDANT...........DATE...............

.................................CHECKED...........DATE...............

.................................APPROVED...........DATE...............

.................................FILE...........DATE...............

Fig. 1.—Relay location slip.

INDUCTION OVERLOAD RELAYS.
PLUNGER OVERLOAD RELAYS.

Adelaide Electric Supply Co., Ltd.

Substation Dept.

From *R T M* **Relay Test Record**

To SS.S.

Make *G.E.* Type *IB.1* Coy. No. *532*

Rating *50* cycles *5* amp. Range *4–10* amp.

Indicating coil rating *2·0* amp.

TEST PROCEDURE

(1) Make a careful inspection

Were there any mechanical defects? *Zero error*

Were internal connections and wiring correct? *Yes*

(2) Did relay function correctly when operated on all current taps? *Yes*

(3) Were contacts in good condition after six operations? *Yes*

(4) Calibration of relays (tabulate results below).

Lever setting	Current tap	Before adjustment							After adjustment						
		Current flowing, amp.													
		Minm.	6	10	12	15	20	40 *	Minm.	6	10	12	15	20	40 *
		Time (sec.) to close contacts													
1	4		0·84		0·46		0·36	0·3		1·0		0·5		0·4	0·3
2	5			1 06		0·8					1·2		0·88		
3	6				1·66							1·8			
4	8				3·24							3·6			
5	10					4·15	2·72						4·5	2·94	

NOTE.

1. Minm. is the minimum current to close contacts.
2. * is a point on the curve where the operating time is practically constant and is independent of the current flowing.

Insulation test *1 000 volts O.K.*

REMARKS *Overhauled* Test by *D.B.* Date *25.1.39*

Contacts burnished Test Checked by ____ Date ____

Tested Approved ____ Date ____

Zero adjusted Entered and Filed ____ Date ____

Fig. 2.—Test record of inverse time relay.

POWER DIRECTIONAL RELAY TEST RECORD

Adelaide Electric Supply Co., Ltd.

Substation Dept.

Make *G.E.* Type *I B-1* Coy. No. *532*

Rating *50* cycles *5* amp. *110* volts, Range *4–10* amp.

Indicating-coil rating *2·0* amp. ____

TEST PROCEDURE.

(1) Make a careful inspection. Were there any mechanical defects? *Hair spring broken*

Were internal connections and wiring correct? *Yes*

(2) Did relay function correctly when operated on all current and potential taps? *Yes*

(3) Were contacts in good condition after several (say 6) operations? *Yes*

(4) Calibration of relays (tabulate results below).

ZERO TORQUE TEST

As found As left

Phase	Amp.	Volts	Does disc turn?	Phase	Amp.	Volts	Does disc turn?
A		O		A	*50*	O	*No*
	O				O	*50*	*No*
B		O		~~B~~		O	
	O				O		
C		O		~~C~~		O	
	O				O		

OPERATION TORQUE TEST

As found As left

Phase	Amp.	Volts	Time	Phase	Amp.	Volts	Time, cycles
A				*A*	*30*	*110*	*3*
					30	*2*	*42*
B					*1·0*	*110*	*18*
C					*5·0*	*5·0*	*78*

INSULATION TEST. *O.K.*

Remarks:—

Hair spring replaced

Test by *D.B.* Date *25.1.39*

Checked ____ Date ____

Approved ____ Date ____

Filed ____ Date ____

Fig. 3.—Test record of directional relay.

their current transformers to simulate fault conditions. The current is obtained from a portable low-voltage transformer (Fig. 4) capable of passing up to 3 500 amp. This method of testing ensures that any errors in the current transformers are taken care of in the settings of the relays.

The settings of relays are co-ordinated by calculations performed with the assistance of a locally-made d.c. calculating table (Fig. 5, Plate 1, facing page 492). Calculations are made whenever any additions to the generating plant or extensions of the transmission circuits occur. The time settings of relays are checked with an

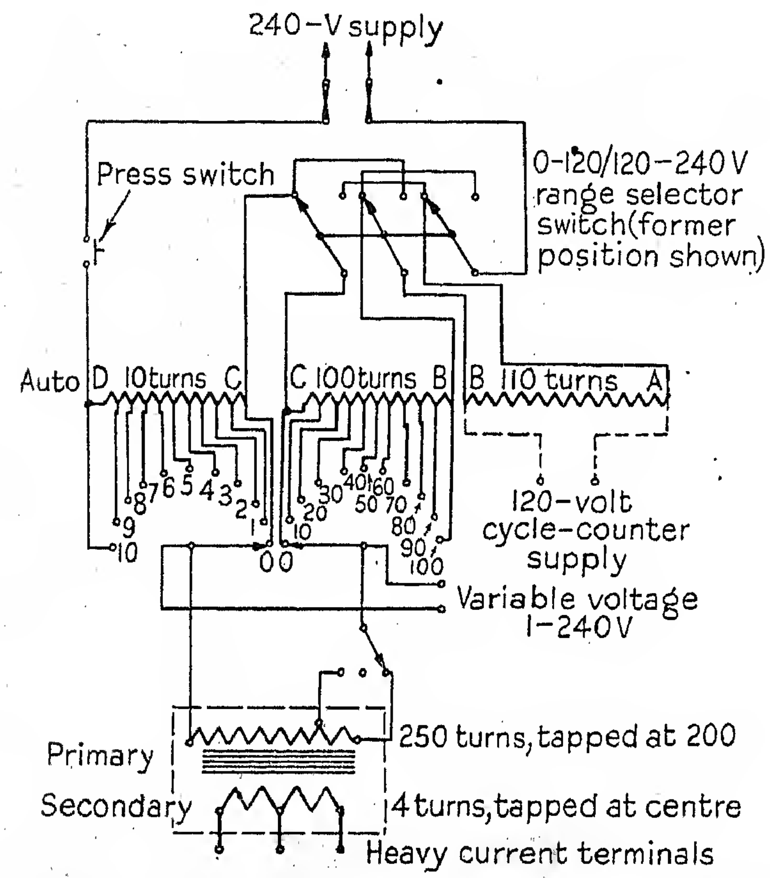


Fig. 4.—Combined auto-transformers and double-winding transformers for testing leakage and other relay circuits carrying currents up to 3 500 amp.

automatic cycle-counting device which starts as soon as the current transformer is energized, and stops when the trip circuit closes. Stop-watch methods are of no use for this class of work. Relays are tested and set to operate at the correct time-delay with a current of the same order as the short-circuit with which they may have to deal under fault conditions.

RELAY MAINTENANCE

Relays are inspected and tested every 4 months. A check is first made on the condition of the relay " as found," i.e. before the cover is taken off or the moving parts are disturbed in any way. A small transformer, shown in Fig. 6 (Plate 1) and Fig. 7, giving up to 15 amp. and 20 volts. is connected to the alternating-current terminals of the relay without disconnecting the current-transformer leads. A small 3-volt dry-cell battery with switch and indicating lamp in circuit is connected to the trip-circuit terminals of the relay without disconnecting the trip circuit but with the oil circuit-breaker in the open position. Where it is preferred to keep the oil circuit-breaker closed, the trip-circuit fuse is drawn during the test. An alternating current just above the pick-up value is passed through the operating coil, and the contacts are gently closed. The battery circuit is then closed, and if the contacts are in good order the indicating lamp lights up. The cover of the relay is then removed and the contacts are closely examined. If in good order they are not touched, but if burnt or tarnished they are polished. Prior to the introduction of testing with the 3-volt battery a number of contact troubles were experienced and an investigation was made with the aid of photomicrographs to ascertain the cause of the trouble. Figs. 8–13 (Plate 2) show a few examples.

These tests indicated that whatever method of polishing contacts was adopted there was a chance of foreign

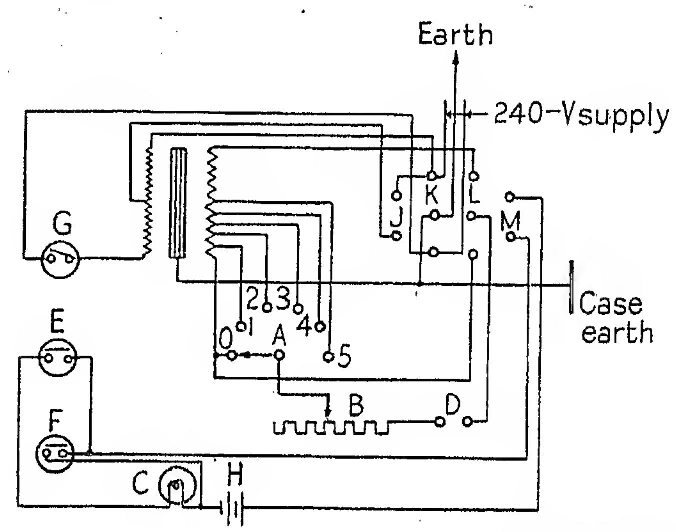


Fig. 7.—Circuit diagram of relay testing transformer.

A. Secondary tapping switch.
B. Carbon-pile rheostat.
C. Red indicating lamp.
D. Ammeter terminals.
E. Press switch in lamp circuit.
F. Press switch in relay contacts circuit.
G. Tumbler switch in 240-volt supply circuit.
H. 3-volt dry battery (two torch cells).
J. 110-volt supply for cycle counter.
K. 240-volt supply points.
L. 0–10 or 0–20-volt transformer secondary to relay coil.
M. Battery supply to relay contacts.

matter remaining on the surface, and so preventing the contacts from closing. The trouble was probably accentuated by the use at that time of only 32 volts on most of the tripping circuits. With a higher voltage the contacts might pass current but would probably burn badly. During the investigation it was found that rounded contact surfaces gave less trouble than flat ones, and that surfaces burnished with a steel tool retained their polish longer and burned much less than surfaces finished in any other way.

For polishing contacts during the routine inspection a " 0000 " emery paper is now used and the polishing is finished off with chamois leather. Tools are made by glueing the emery paper or chamois to thin strips of wood. After polishing, a rubber bulb with a fine nozzle is used to blow off any particles of abrasive or chamois which may have adhered to the contacts. An electric torch and a magnifying dental mirror are used for examining the contact surfaces.

As a result of the improved technique in contact maintenance and the use of the 3-volt test on every relay after

SHEET No.................................

ADELAIDE ELECTRIC SUPPLY CO., LTD.
SUBSTATION DEPT.

From..

To ....

RELAY INSPECTION REPORT

.... Inspection of relays at ....Substation.

Date of inspection:..

Line, circuit, and phase	Relay type	Tests of contacts and pick-up		Result of trip tests	Insulation		Potential		
		First test	Final test		C.T. to earth	C.T. continuity			

A. Is all panel wiring in good condition? ....

B. Are all relay and trip plunger settings correct? ....

C. D.C. wiring insulation. Pos. to E..........................Neg. to E..........................Pos. to Neg. ....

Describe fully any faulty condition found, and remedy used:—

Tested .... Checked.. Approved..

Fig. 14.—Report form for relay inspections.

the mechanic has finished installing or overhauling, contact troubles have been eliminated.

The results of the relay inspections are recorded on forms similar to that shown in Fig. 14, which are placed in the file kept for each substation. Every 3 years each relay is brought into the test room for a complete overhaul, and the results of this examination and test are recorded on slips (Figs. 1, 2 and 3) which are pasted into the relay registers. The results of all inspection reports are tabulated annually and analysed to show the kind of trouble that is being checked by the maintenance work, and to expose the weaknesses of various types of relays and their associated equipment. The results of this analysis for the years 1935–38 are shown in Table 3.

Comments on Table 3

(1) General.

The number of inspections was reduced for the years 1937 and 1938 owing to the pressure of new work and the extension of the time between inspections from 3 to 4 months.

A marked reduction in relay contact troubles was noted, due to: (i) Improved cleaning technique and use of contact-testing device. (ii) Certain relay contacts changed from copper to german silver. (iii) Certain relay contacts now domed and flat instead of having parallel surfaces.

(2) Major defects.

(*a*) 1935 Burn on contact surface and inadequate contact pressure combined to prevent relay from tripping oil circuit-breaker.
Contact finger of plunger-type relay found to have inadequate pressure. Fingers now split and reinforced.

1938 Dirty auxiliary switch contacts prevented oil circuit-breaker from reclosing.

(*b*) 1935 Differential current-type relay, previously tested by hand, was found to have inadequate contact pressure when closed electrically.

(*g*) 1936 White horn-fibre had been used for lining bobbin cheeks of oil-circuit-breaker trip coils. Corrosion occurred at some points of contact between lining and winding.

1936 7·6-kV mains fouled indicating-system con-

Table 3.—Relay and Wiring Defects Discovered During Maintenance Inspections in the Years ending 31st August, 1935, 1936, 1937 and 1938

Ref.	Year	1935				1936				1937				1938			
	Total number of relays inspected ..	1 732				1 771				1 256				1 492			
	Nature of defect	Major*		Minor†		Major*		Minor†		Major*		Minor†		Major*		Minor†	
		No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
(a)	Tarnished or burnt contacts	2	0·112	12	0·674	—	—	7	0·396	—	—	—	—	1	0·067	—	—
(b)	Badly adjusted contacts ..	1	0·056	2	0·112	—	—	7	0·396	—	—	—	—	—	—	—	—
(c)	Internal relay faults ..	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	0·134
(d)	Low *IR* of C.T. or circuit ..	—	—	3	0·168	—	—	3	0·169	—	—	2	0·159	—	—	4	0·268
(e)	Low *IR* of trip-coil circuit..	—	—	2	0·112	—	—	2	0·113	—	—	—	—	—	—	2	0·134
(f)	Faulty-operation indicator..	—	—	2	0·112	—	—	2	0·113	—	—	—	—	—	—	2	0·134
(g)	O.C. in trip-coil circuit ..	—	—	—	—	2	0·113	—	—	—	—	—	—	1	0·067	—	—
(h)	Sluggish disc ..	—	—	2	0·112	—	—	—	—	—	—	1	0·079	—	—	3	0·201
(j)	Sluggish trip-coil plunger ..	—	—	—	—	—	—	1	0·056	—	—	—	—	—	—	—	—
(k)	Loose fittings or connections	2	0·112	2	0·112	—	—	—	—	—	—	1	0·079	—	—	2	0·134
(m)	Not included above ..	—	—	—	—	—	—	—	—	—	—	—	—	1	0·067	1	0·067
	TOTAL ..	5	0·28	25	1·40	2	0·113	22	1·24	—	—	4	0·318	3	0·20	16	1·07

* A major defect is one that would most probably cause an incorrect system operation by (1) the isolation of a healthy circuit, or (2) a failure to isolate a system fault.
† A minor defect is one which is very unlikely to cause an incorrect operation.

ductors and broke down indicating-relay insulation to local wiring.

1938 Open-circuit developed in relay series resistor wound with No. 40 S.W.G. resistance wire.

(k) 1935 Bush of relay riser-rod loose on spindle.
Rivet of drum-switch contact worked loose, permitting intermittent open-circuit.

(m) 1938 Oil circuit-breaker wrongly wired to leakage relay.

(3) Minor defects.

(a) and (b) See (1) and (2), above.

(c) 1938 Plungers of differential-type relay fouling guide-tubes.
Internal connections of relay found to be corroded.

(d) Condensation on slate panels.
Water entering oil circuit-breaker via faulty bushing cap (outdoor oil circuit-breaker).
Fracture of lead sheath of control cable.
Terminal box not watertight (outdoor oil circuit-breaker).
Current-transformer leads jammed by oil circuit-breaker mechanism cover.

(e) Condensation on slate panels.
Terminal lug of one lead penetrating insulation of adjacent lead.
Relay-cover bearing on indicator coil.

(f) Oil-circuit-breaker trip-coil current insufficient to operate relay targets (especially in case of "interphase" faults where several relays share the tripping current).

(h) Sticky oil in top bearings.
Disc incorrectly located relative to damping magnets.
Iron filing lodged in air-gap.

(k) Loose damping-magnet brackets.
Loose shunt-fuse contacts.
Loose plunger grub-screw, allowing plunger to move freely on adjusting screw.

(m) Relay cases not earthed.

RELAY FAULTS

As a result of the experience obtained, the following faults in the design or construction of some modern relays have been noted.

Induction Overcurrent and Directional Relays

Make A.

(1) Terminal-bushing insulating blocks are weak mechanically and electrically. Several breakdowns experienced.

(2) Cases give poor accessibility for maintenance as received. An improvement was effected by inverting the covers. (Makers are altering the design to improve this.)

(3) Bare internal wiring with small clearances and considerable risk of short-circuits.

(4) Current tap plug-sockets were mounted on fibre material, which loosened contact on shrinking. This has been rectified in a later design.

(5) Trip indicators operated mechanically by the disc

imposed serious extra load and affected time of relay at near pick-up current.

(6) Time-lever scale held on by two screws through over-size holes, resulting in inaccurate location of time scale.

(7) Parallax errors due to time-lever pointers being too far away from time scale.

Make B.

(1) Inconsistent times when testing, owing to heating of coil being much more marked than in other makes.

(2) No separate trip indicator on instantaneous short-circuit attachment.

(3) Tripping current carried through disc return spring; this is undesirable.

(4) Parallel-faced contacts burn badly (see Figs. 8–13). Later models have domed contacts.

(5) Cup-type top bearings in directional elements wore rapidly owing to vibration. Pin-type bearings were therefore substituted. Makers now putting in pin type.

(6) No separate holding studs. Using terminal studs for holding relay causes breakage of the stud insulating blocks. Detachable studs much preferred.

Drum-type Multi-contact Relays

Make A.

Faults (1) and (3) same as for this maker's induction-type relays.

(4) Catch not "hooked" enough. Several false trips were caused by vibration of panels, due to unstable latching.

(5) One driving spring only on drum. Second spring improves operation considerably, and increases factor of safety.

Attracted-Armature Gravity-Operated Multi-Contact Relay

Make C of this type is very susceptible to operation by vibration due to unstable latching.

General

It will be noticed that unstable latching due to faulty construction has been a source of considerable trouble with multi-contact relays.*

GENERAL MAINTENANCE WORK

Circuit-breakers are overhauled once a year, and particular attention is given to the auxiliary switches and trip coils. A close examination is made of the latching and tripping mechanisms to ensure that they function correctly when a tripping impulse is received from the relay, as a surprising amount of trouble has been experienced with oil-circuit-breaker latching mechanisms supplied by reputable manufacturers.

It has been found advantageous to rewind the trip coils of some breakers in order to reduce the tripping current to about 3 amp., thereby minimizing the burning of relay contacts. The results of these circuit-breaker inspections also are tabulated and analysed annually.

The wiring of relays and circuit-breakers is tested every 4 months for insulation-resistance and continuity. Lead batteries are inspected monthly in the metropolitan sub-stations, and alkaline batteries half-yearly in the country ones.

Neon glow lamps permanently connected on the relay panel are used as indicators to show that the 110-volt circuits of voltage transformers are energized, so that a blown fuse is quickly detected.

OPERATING RESULTS

Some reference can now be made to the results which are obtained from the relays and protection system when dealing with actual faults. These results are analysed annually, and in Table 4 is shown the percentage of accuracy obtained from the relays during the years 1935–38. This Table is based on the number of individual relay operations, which of course is larger than the number of faults dealt with, as two or three relays may have to operate to clear a fault. Failures to operate are practically unknown, but are treated as incorrect operations when calculating the percentages.

* See the author's contribution to the discussion on "Fire Protection in Major Substations," *Journal I.E.E.*, 1937, **81**, p. 717.

Table 4†

ANALYSIS OF RELAY OPERATIONS IN THE YEARS ENDING 31ST AUGUST 1935, 1936, 1937 AND 1938

	1935			1936			1937			1938		
	33 kV	7·6 kV	Total	33 kV	7·6 kV	Total	33 kV	7·6 kV	Total	33 kV	7·6 kV	Total
Total number of operations	197	39	236	59	76	135	100	95	195	124	51	175
Number correct	193	38	231	57	75	132	99	92	191	120	50	170
Number incorrect	4	1	5	2	1	3	1	3	4	4	1	5
Number doubtful	—	—	—	—	—	—	—	—	—	—	—	—
Percentage correct	97·9	97·4	97·8	96·6	98·6	97·7	99	96·8	97·9	96·8	98·0	97·3
Incorrect due to: Faulty relay	4(*a*)	—	4	—	—	—	—	1(*d*)	1	—	—	—
Incorrect due to: Incorrect relay setting	—	1(*b*)	1	1(*b*)	1(*b*)	2	—	—	—	4(*f*)	—	4
Incorrect due to: Human element ..	—	—	—	1(*c*)	—	1	1(*c*)	2(*e*)	3	—	1(*g*)	1

† The references (*a*), *b*), *c*), etc., are to the "Comments" on page 492.

Comments on Table 4

(a)	3.11.34	It was suspected, from the badly burned oil-circuit-breaker contacts, that the leakage relay was slow in tripping No. 91 section breaker. This allowed the line breaker at Osborne, which was feeding a healthy section, to trip. Subsequent tests did not reproduce the conditions.
	7.11.34, 21.2.35, again 21.2.35	Croydon. Three operations due to faulty equipment, now discarded.
(b)	9.8.35	Synagogue Place substation. Induction relay had been given a lever setting of 0·35, which gives an inadequate margin of contact separation. When panel was jarred during maintenance, relay operated.
	14.2.36	(33 kV) Fisher Place substation. Inadequate latching of leakage relay (gravity type).
	15.5.36	(7·6 kV) Synagogue Place. Inadequate latching of leakage relay. Trigger found to be riding on striker pin.
(c)	3.6.36	Fisher Place. Mechanic omitted to draw negative fuse, and oil circuit-breaker tripped when relay was operated on test.
	11.1.37	Fisher Place. Member of construction staff dropped piece of timber against panel, causing leakage relay to operate by vibration.
(d)	2.1.37	Aroona Road. Contacts of directional overcurrent relay locked closed on through fault, causing an incorrect operation when direction of load power flow was later reversed.
(e)	3.12.36 again 3.12.36	Croydon. Vibration, set up by men working on switchboard panel, caused pallet switch in a directional relay to make contact.
(f)	2.9.37	(3 operations). Directional relays on No. 94 oil circuit-breaker slower than those on No. 91 for fault on Gawler "B" line, owing to poor current-transformer ratios at Gawler. These troubles now obviated by alteration to current transformers.
	25.2.38	Men breaking up concrete floor operated lightly latched leakage relay by vibration. Relays now altered to give positive latching.
(g)	10.6.38	Men working on panel tripped relay.

Methods of Analysis

Table 4 is not directly comparable with any of the tables in E.R.A. Report F/T94,* which are compiled on the basis of the number of disturbances correctly or incorrectly dealt with by the protection system. Table 5, however, is compiled on the latter basis, but still differs from the tables in the E.R.A. Report in that all incorrect operations or "false trips" are recorded as faults or disturbances of the system. In the author's opinion the method of analysis used in the E.R.A. Report is seriously misleading. By including only the correct operations and the failures to trip when calculating the protective efficiency we have the anomalous position that a system for which a high protective efficiency is claimed, may have more incorrect operations than correct ones. Such a method is quite unsuitable for the use of undertakings which desire a criterion of the efficiency of their protective systems. All false trippings due to instability of relays, wrong settings, or carelessness on the part of the staff responsible for maintenance, should be shown as a reduction in protective efficiency. Serious disturbances equivalent to those caused by faults can be caused by relays which trip-out circuits when they should not do so, and such operations should be shown as a reduction of protective efficiency. The protective efficiency can be satisfactorily defined by the following expression:—

$$\frac{\text{Number of protection operations correct} \times 100}{\text{Number of protection operations}}$$

This method has been used in calculating the values given in Tables 1 and 5.

In preparing the data for Table 5 the following rules have been observed: An operation is recorded as correct if the various relays operate in accordance with the designed plan, even if circuits are tripped unnecessarily, as, for instance, in case of overlapping of the fields of protection. An operation is taken as incorrect if the fault is not cleared by the appropriate relays and breakers, even if cleared correctly by the back-up protection. Circuits tripped by mistake or carelessness of the men engaged on switchgear and relay installation and maintenance are counted as incorrect operations. (Installation work is done by the staff of the undertaking.) Failures to trip are counted as incorrect operations. Failures to trip due to faults in circuit-breakers, instrument transformers, batteries, and wiring, are included.

The results shown for the last 2 years in Table 5 are not as good as they should be, owing to the large amount of reconstruction work carried out in the substations and the employment of additional untrained staff.

Comments on Table 5

(*a*) Three of these failures occurred on an old type of relay used on special equipment which has since been discarded.

(*b*) Fault on No. 3 transmission line. In this case, No. 1 line "A" circuit was out for maintenance, and a double-circuit fault on No. 3 line reduced the number of main lines available to three circuits. The system was running near its peak load, and the system section switches opened on overload, through being set too low for the abnormal condition.

(*c*) Relay was knocked while panel was being cleaned; relay operated by vibration.

(*d*) Faulty latching of switch mechanism.

(*e*) Faulty internal contact in shunt fuse.

(*f*) (i) Relay panel knocked; relay operated by vibration. (ii) Tester omitted to disconnect tripping supply prior to maintenance test on relays.

(*g*) Faulty latching on busbar-leakage relay.

(*h*) An overcurrent relay, in series with a directional relay, failed to release after a through fault; and.

* *Journal I.E.E.*, 1936, **97**, p. 541.

Plate 1

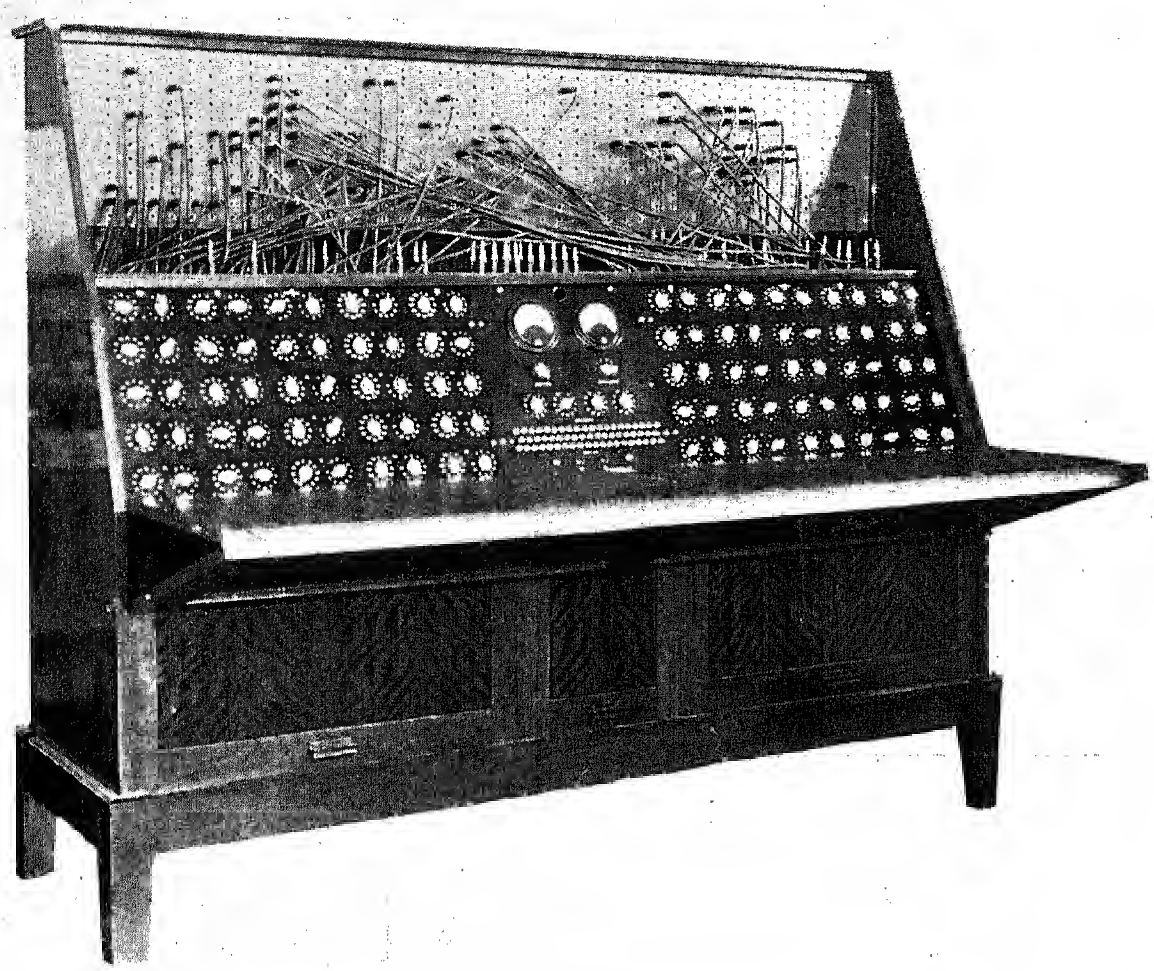


Fig. 5.—System calculating table.

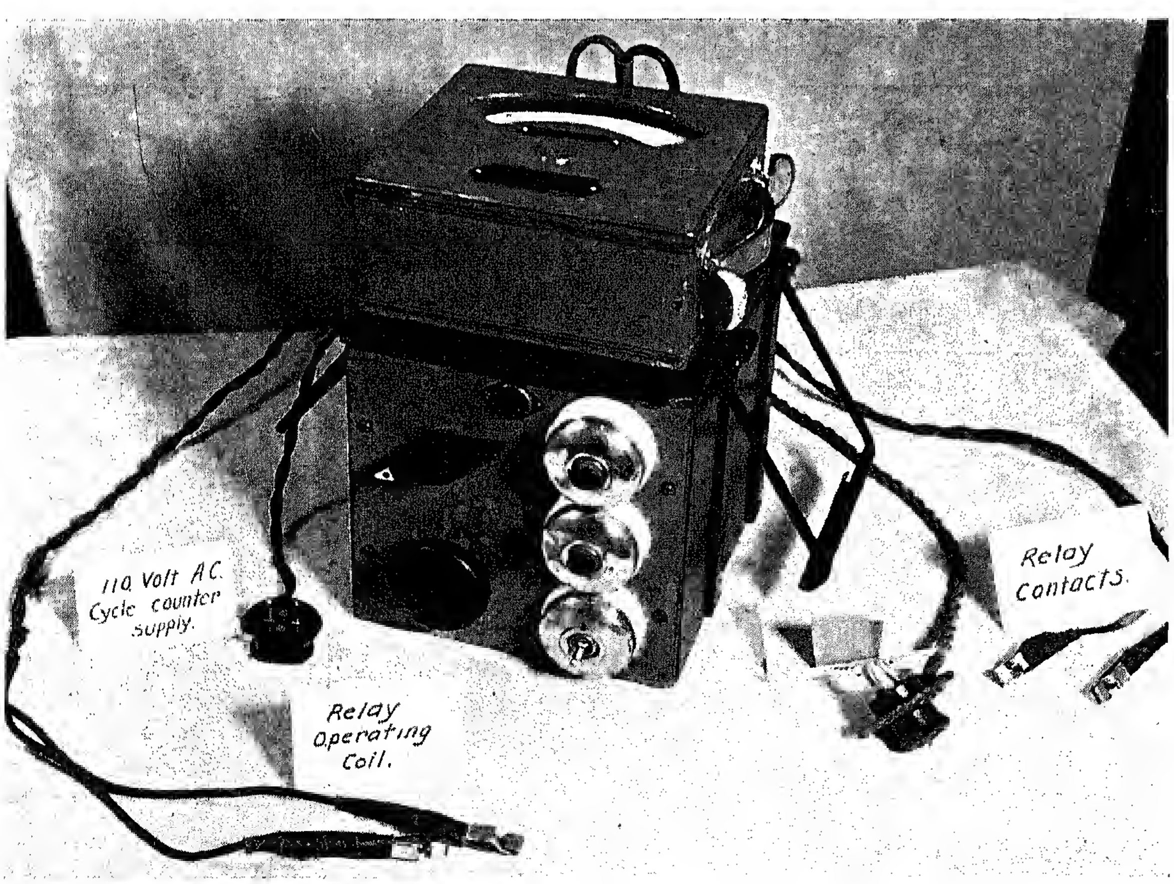


Fig. 6.—Relay testing transformer.

Plate 2

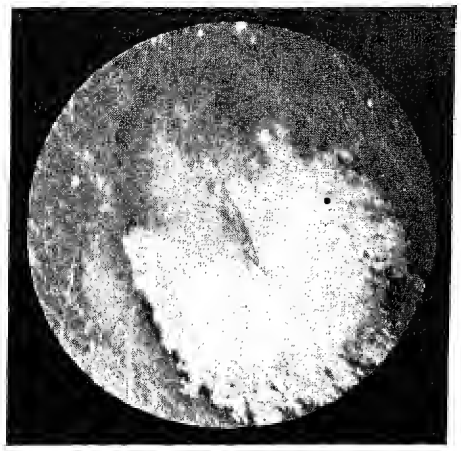


Fig. 8.—Contact of relay returned from service, showing excessive burning (magnification 75).

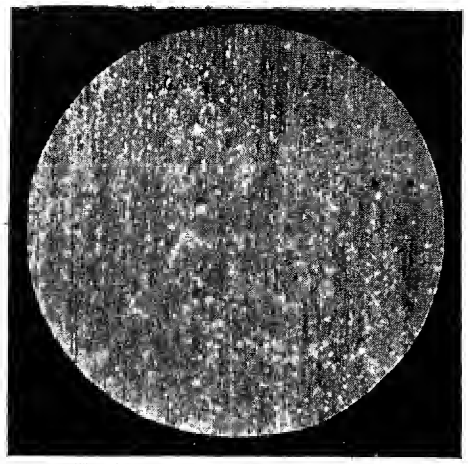


Fig. 9.—Silver contact after rubbing with abrasive paper, showing embedded particles (magnification 75).

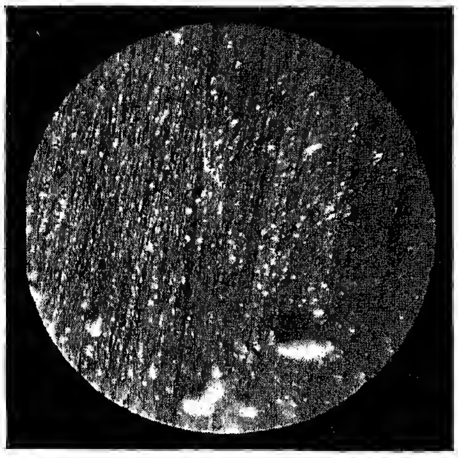


Fig. 10.—Silver contact, showing loose particles of abrasive forming lumps (magnification 150).

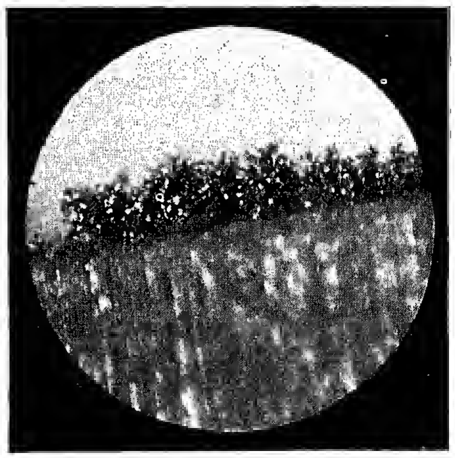


Fig. 11.—Accumulation of abrasive crystals at edge of contact (magnification 75).

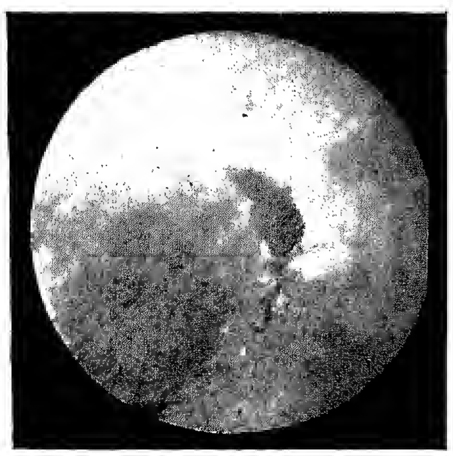


Fig. 12.—Moving contact of relay returned from service, showing accumulation of block rouge (magnification 150).

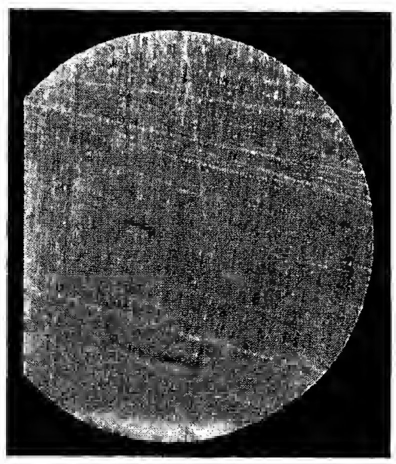


Fig. 13.—Chamois - leather fibre left after wiping contact (magnification 75).

Table 5*

SYSTEM PROTECTION OPERATIONS: YEARLY RETURNS FOR 1935, 1936, 1937, AND 1938

	1935				1936				1937					1938				
	33 kV	7 kV		Total	33 kV	7 kV		Total	33 kV	7 kV			Total	33 kV	7·6 kV			Total
		Relay	Shunt fuse			Relay	Shunt fuse			Relay	Shunt fuse	Reclose			Relay	Shunt fuse	Reclose	
Total	57	21	40	118	35	29	29	93	44	35	23	8	110	60	32	48	22	162
Correct	52	20	37	109	33	28	29	90	44	28	22	7	101	52	26	47	19	144
Incorrect	5	1	3	9	2	1	—	3	—	5	1	1	7	8	6	1	3	18
Doubtful	—	—	—	—	—	—	—	—	—	2 (n)	—	—	2	—	—	—	—	—
Percentage correct	91	95	93	92	94	97	100	97	100	80	96	87	92	87	81·5	98	86·3	89
Incorrect due to: Faulty o.c.b. mechanism	—	—	1 (d)	1	—	—	—	—	—	—	1 (m)	—	1	—	3 (s)	—	1 (w)	4
Faulty relay mechanism	4 (a)	—	—	4	—	1 (g)	—	1	—	1 (h)	—	—	1	—	—	—	—	—
Faulty relay settings	1 (b)	—	—	1	—	—	—	—	—	—	—	—	—	2 (p)	—	—	1 (x)	3
Human element	—	1 (c)	—	1	2 (f)	—	—	2	—	2 (j)	—	—	2	4 (q)	1 (t)	—	—	5
Other reasons	—	—	2 (e)	2	—	—	—	—	—	2 (k)	—	—	2	1 (r)	2 (u)	1 (v)	1 (y)	5
Cause not found	—	—	—	—	—	—	—	—	—	2 (n)	—	1 (o)	3	1 (z)	—	—	—	1

* The references (a), (b), (c), etc., are to the "Comments" on page 492.

when the power subsequently reversed, the directional relay tripped out the switch.

(j) Vibration, caused by men working on relay switchboard, operated relay.

(k) (i) Three-phase busbar fault in transformer house supposed to have insufficient earth current to operate leakage protection. All sources of supply disconnected by back-up protection. (ii) Faulty operation of special equipment which has since been discarded.

(m) Oil circuit-breaker found open without known reason; faulty latching suspected.

(n) (i) No. 742 oil circuit-breaker found open after stormy weather during which a number of kicks were experienced, which could not be accounted for. (ii) No. 742 oil circuit-breaker found open without known reason. Latching overhauled.

(o) Oil circuit-breaker failed to reclose after fault. When tried 10 minutes later it failed to latch, but on a second try it closed, thus suggesting that the fault was mechanical.

(p) (i) Relays on No. 94 oil circuit-breaker slower than those on No. 91 for a fault on Gawler "B" with minimum generating plant on busbar. Lost Gawler "A" and "B" lines. (ii) East Terrace: men breaking concrete floor operated lightly-latched leakage relay by vibration.

(q) (i) Wrong operation at Gilbert Place; oil-immersed switch handle moved to "earth" position by mistake. (ii) Incorrect switching sequence at Willcox Street caused loss of supply at Gilbert and Post Office Place substations. (iii) Breaker accidentally tripped by mechanic.

(r) Fisher Place. While leakage relay was being tested, entire station was shut down owing to a mistake in relay wiring.

(s) (i) No. 715 oil circuit-breaker at Croydon did not open on fault, owing to locked toggle. (ii) No. 716 oil circuit-breaker at Aroona Road did not open on fault. Operator slipped while closing breaker on to fault. Main contacts just "made" but auxiliary "a" switch was not quite closed, so that breaker was not electrically trip-free. (iii) No. 760 oil circuit-breaker at Woodville, in opening due to fault, formed a copper head on cross-bar, which prevented breaker from tripping free when auto-reclosed on to fault; due to bad design of arcing contacts on new equipment.

(t) Nut of relay cover dropped on to oil circuit-breaker trip plate.

(u) (i) Trip coil of radial feeder oil circuit-breaker was wrongly connected to leakage relay. (ii) Hindley Street: vibration of panel caused relay to operate.

(v) No. 863 oil circuit-breaker opened owing to faulty shunt fuse.

(w) St. Vincent Street feeder breaker failed to reclose owing to faulty mechanism.

(x) No. 863 oil circuit-breaker at Richmond did not reclose automatically, owing to incorrect adjustment of timing relay.

(y) No. 715 oil circuit-breaker at Croydon did not reclose automatically, owing to an open-circuit in timing-relay wiring.

(*z*) Operation of No. 108 oil circuit-breaker at Birkenhead. An earth fault was found on the pallet switch of an induction-type relay, but this in itself would not trip the breaker. No definite cause has been found, but it is suspected that the operation was the result of a breakdown of the insulation due to an inductive kick from the closing solenoid of another breaker which was being operated at the time, causing the pallet switch to operate.

CONCLUSIONS

We may now summarize the requirements for successful operation of the protective equipment of electricity undertakings, as follows:—

(1) Correct design of the protective system, and the selection of suitable relays.
(2) Bench tests and inspection of relays before installation.
(3) Careful installation of relays and wiring.
(4) Setting of relays in accordance with calculated short-circuit values at various parts of the system, with maximum and minimum generating plant connected.
(5) Tests simulating fault conditions to verify performance.
(6) Routine inspection and maintenance of relays and associated equipment several times per annum.
(7) Annual overhaul of circuit-breakers.
(8) Bench test of relays every 3–4 years.
(9) Records of all inspections and tests.
(10) Inquests on all protection operations, and reports on their correctness or otherwise in comparison with the design.
(11) Tabulation and comparison of inspection and operation reports.
(12) Modification of the protective system and the relay settings from time to time to meet load growth and extensions of the transmission and distribution network.

In view of the important duty they have to perform, one would like to see protective-relay systems approach much nearer 100 % efficiency than they do at present. In railway signalling relays, for instance, the percentage of error has been reduced to a small fraction of 1 %, as is also the case with telephone relays in the automatic exchanges. At the present time, however, in any large power system, an accuracy of over 90 % in relay operation is regarded as reasonably good. There are several reasons why the accuracy of protective relaying falls so far below that obtained in railway and telephone work. In those cases the relays are in continual operation, many times a day, and faults in design and construction are soon detected and eliminated. Protective relays, on the other hand, operate at very infrequent intervals and perhaps only after standing still for months, or, if neglected, for years. Another reason is that signal and telephone relays operate under closely controlled conditions, whilst protective relays have to deal with a wide range of fault conditions, sometimes accompanied by surges. In spite of this, however, the accumulation of experience and research in the relay field, combined with careful installation and maintenance, will undoubtedly make possible, in the future, a nearer approach to 100 % efficiency.

ACKNOWLEDGMENTS

The author is indebted to Mr. F. W. H. Wheadon, Member, managing director of the Adelaide Electric Supply Co., Ltd., for permission to publish data concerning the Company's protective system.

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 2ND FEBRUARY, 1940

Mr. F. J. Lane: The author begins by suggesting that lack of maintenance is largely responsible for the poor results that are obtained from protective gear. In an effort to check this statement I recently examined 83 cases of incorrect relay operation. I found that 28 faults were due to design defects, 18 to defects in construction and 20 might have been eliminated by careful maintenance. Of the remainder, 11 were due to the human element and 6 were unexplained. Thus, although lack of maintenance is an important contributory factor, it is not necessarily the most important factor affecting protective-gear performance.

Regular maintenance work on protective equipment must be regarded as essential because (*a*) it ensures freedom of operation of the apparatus; (*b*) it provides opportunities for detecting incipient faults; (*c*) it provides opportunities for detecting defects in construction of relays, and design of the protective equipment as a whole; (*d*) it provides the staff with a basic knowledge of the equipment, enabling them to diagnose more easily the cause of troubles occurring during system fault conditions.

If routine maintenance work is to be carried out efficiently it is imperative that from the very beginning the protective equipment should be planned with the need in view for adequate facilities for testing and inspection. Relay panels, for example, should be located in accessible positions, and relays should be well spaced and should not be set below a certain minimum height (18 in. is suggested) on the relay panel. Covers should be dust-proof and yet provide facilities for inspecting the general assembly without removing the relay from the panel. Relay terminals should be well spaced to give adequate clearance between adjacent Ross–Courtenay wiring terminations, and should be large enough to withstand the forces normally applied when tightening connections. For testing purposes it is important to have good facilities for the isolation of each equipment from the general body of small wiring. The author objects to the provision of test links in current-transformer circuits, but experience in this country has shown that adequate maintenance of the more complex equipments in use here is not possible without them; they should be mounted on the front of the panel so as to permit the tester to connect and watch his instruments while observing the various relay operations.

A typical assembly of test links is shown in Fig. A. These permit isolation of d.c. circuits, insertion of instru-

ments in current-transformer secondary circuits, and measurement of secondary voltages.

An alternative to the test link is the "test switch," an example of which is illustrated in Fig. B. When the switch is in the normal position the current, voltage and d.c. circuits to the relays are completed through robust contacts. On turning the switch to the "test" position the relay current coils are isolated, the current-transformer secondary windings are short-circuited, and the voltage and d.c. connections are isolated. Test sockets are then available on the panel to permit injection tests to be made on the relays without risk of tripping adjacent equipments. If separate test switches are provided for the main and the back-up protective units, relays can be tested and calibrated while the associated primary circuit is kept on load, an important advantage where spare transmission capacity is limited or on occasions when there is difficulty in co-ordinating the "primary" and "protective gear" maintenance programmes.

Small wiring is also well worthy of attention in the design and construction stage. For the d.c. circuits the preparation of a simplified, or key, diagram is invaluable, as it gives a clear picture of the circuit arrangement and enables the tester to see immediately the possible effect of removing a link or a connection; so-called "sneak circuits" have accounted for far too many incorrect tripping operations during testing. Open-circuits arising from electrolytic corrosion can be largely eliminated by arranging that relay coils are not normally connected to the positive side of the battery. In the a.c. circuits maintenance testing can be eased by providing each set of connections (say, each set of current-transformer or voltage-transformer secondary circuits) with its own return earth lead, and by earthing each such circuit at one point only. Terminal boards should be accessible, and I agree with the author that all wiring terminations should be clearly numbered to correspond with the associated diagram of connections. In his Inaugural Address* the President (Mr. Johnstone Wright) has suggested the adoption of a standard system of numbering or marking terminations, to be applicable whatever the manufacturer.

If points similar to those mentioned above are watched during design and manufacture, efficient maintenance becomes a possibility. The next step is the selection and training of testing staff. Protective-gear assistants should preferably have had works experience in the design, construction and testing of current transformers and relays. They should be encouraged to take an interest in protective gear as complete units, not merely in the individual relays; manufacturers could help materially to ensure clear understanding of operation by providing a descriptive pamphlet covering the equipment as supplied, its principle of operation, recommendations as to routine tests, and possibly suggestions as to location of trouble in service. For the purpose of educating staff, commissioning tests are invaluable, as it is then necessary to check through every item in detail—current transformers, small wiring, multi-core cables, relays—and even though this work may be strictly the contractor's responsibility, the local maintenance staff should follow the tests carefully, making their own notes of the results and learning the connection and location of the various components.

Routine testing should be carefully planned, and should be interrupted as little as possible. The author draws attention to the reduction of efficiency which followed the longer maintenance intervals and the introduction of less-skilled staff during a heavier construction programme. Circuit-breaker trip circuits can be tested from associated relays once a month by an engineer who is not necessarily a protective-gear specialist. The author suggests that general tests should be undertaken every 4 months; this must require a large staff, and seems to me unnecessarily frequent as experience here indicates that once every year is sufficient. I do not agree that bench tests are essential every 3–4 years; we have found it quite sufficient to carry out a bench overhaul only when a relay develops a fault which cannot be cleared easily at site.

It is a good plan to arrange for all routine test records to be scrutinized by one person, so that any fault which is applicable to a particular type of equipment can be rectified wherever apparatus of the same kind is located.

The importance of collecting data as to the performance of protective gear in service is now generally recognized. The author complains that the E.R.A. basis, whereby the performance is judged on the number of system faults correctly cleared, is unsatisfactory if the performance of a particular protective system is to be properly assessed.

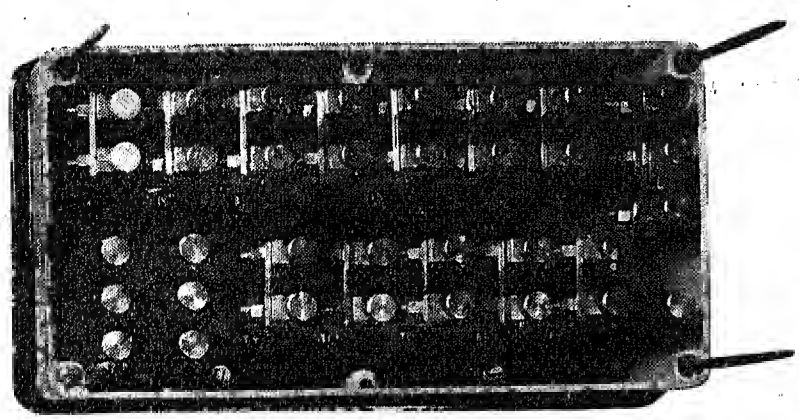


Fig. A.—Typical protective-gear test-link assembly (cover removed).

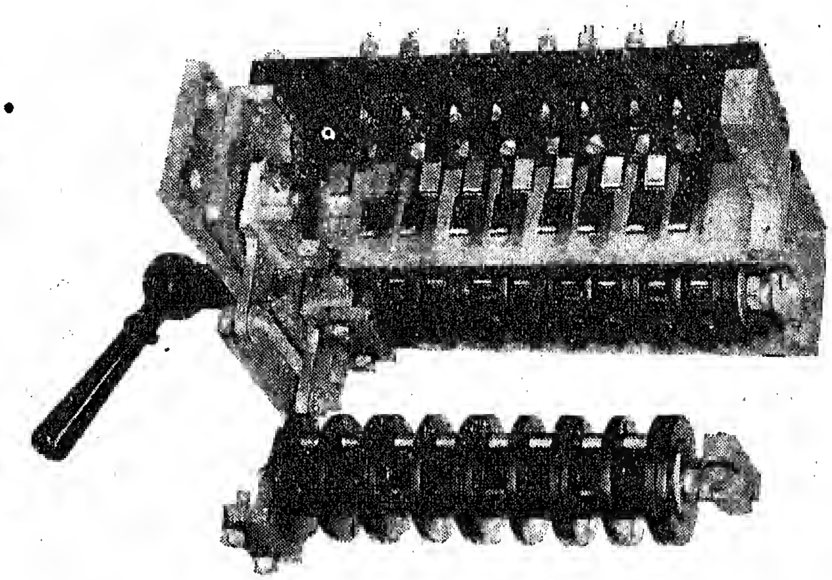


Fig. B.—Protective-gear test-switch assembly for panel mounting, view from below (covers removed).

* *Journal I.E.E.*, 1940, **86**, p. 1.

That is true, but to obtain a performance figure for any particular protective system will require a much more careful analysis of the results than even the author suggests. He includes in his figures the inadvertent tripping of relays by operators, and the inaccurate setting of relays by maintenance staff; these are faults which only in very exceptional cases can be attributed to defects in the protective gear as such.

The justification for the E.R.A. basis lies in the fact that the protective gear is provided primarily to isolate faulty equipment, and therefore its behaviour under fault conditions is the criterion of most general interest. On the transmission circuits of the Central Electricity Board the performance figures obtained during the past 3 years are as follows:

	1937	1938	1939
Total number of faults ..	441	440	598
Faults correctly cleared ..	358	379	543
Percentage correctly cleared ..	85·3	88·5	90·8

In 1939, one district had 91 faults cleared correctly out of a total of 93, or 98 % correct.

The author suggests that performance should be assessed on the basis of the number of relay operations, but it is not clear how these are computed. For instance, is the circuit-breaker trip coil counted as a relay element operating independently; or, with a complicated relay equipment like 132-kV ratio-balance feeder protection, should one include each earth-fault starting element, phase selector, selector contactor, clock rheostat, ratio-measuring element and tripping contactor as an independent relay, making 6 relay units for each correct earth-fault clearance?

As to the possibility of attaining a performance figure of 100 %, it is probable that this figure may be reached where the simpler types of protective gear are employed, but the ideal figure must be treated with extreme caution where the more complex types are involved. For example, it is possible that all types of feeder fault could be cleared with 100 % efficiency if protective equipment of the balanced or Merz–Price type were installed. In actual practice, however, the cost of the necessary pilot cables would be prohibitive on the longer overhead lines, and consequently the responsible engineer would select a cheaper but more complicated arrangement, using directional relays, distance relays, or high-frequency carrier-current interlock equipment. The use of directional relays, employing a comparison of current and voltage, inevitably introduces weakness, not merely because of additional complication but also because there are certain types of primary fault which these relays cannot locate and clear accurately. While, therefore, 100 % efficiency is a desirable aim, supply engineers should appreciate that economic considerations must often limit the choice of equipment to relay systems which, while clearing selectively the majority of fault conditions, will be found wanting in certain of the more complex faults.

Mr. A. J. Gibbons: Probably one fundamental cause of the troubles which have been experienced on systems equipped with protective gear has been the employment of either untrained or unsuitable staff, a subject which is hardly mentioned in the paper. As supply systems increase in complexity, there is a rise in the standard of technical knowledge and skill that is required from the staff. It must be borne in mind that on the technical knowledge of supply system protective-gear maintenance staffs rests a major responsibility for the maximum possible continuity of supply when faults or disturbances occur. The engineer concerned with protective gear must have had a very thorough technical training to enable him to appreciate both the fundamentals and the more detailed functions of the complex schemes with which he is dealing. His training should include experience with heavy plant, and it is especially important that he should be familiar with high-voltage switchgear as well as being thoroughly conversant with relays, instrument transformers and measuring instruments.

A man who fulfils these conditions can be trusted to discover any defects that exist, even if they are only incipient. Such a man will have the skill and inventive ingenuity to improvise tests with any apparatus which may be available, in order to track trouble to its source. He will, of course, have to be adequately paid. It is quite hopeless to attempt to deal with protective-gear maintenance solely by means of instrument mechanics, since the relays in a protective scheme are only a part of a complex whole.

On the system with which I am concerned there is a large amount of h.v. protective gear, protecting some 35 generators, 147 feeders, 126 transformers and 108 coupling equipments; and there are also 32 sets of busbar protection. This gear is maintained by a section of the test department consisting of one protective-gear engineer, a senior assistant, and two junior assistants, all of whom have the status of Associate Member or Graduate of The Institution. We aim at making a site test on every equipment once a year. The duties of the protective-gear section comprise the preparation of protective-gear schemes for new plant; the commissioning of all new plant, including phasing tests; the maintenance of the gear throughout the rest of its life; responsibility for all settings in conjunction with the control department; and the keeping of all records. Generally speaking, failures to trip are completely unknown.

Mr. J. G. Wellings: The author introduces his paper by deploring the performance of certain types of protective gear, and considers that inadequate maintenance is largely responsible. In Table 5, however, for the year 1938 a total of 18 incorrect operations are shown. I think it is wrong to include the 4 due to faulty mechanism of the oil circuit-breaker and the 5 due to the human element. Of the remaining 9 incorrect operations, 3 were due to faulty relay settings, and the remaining 6 are unaccounted for; so that, adopting my view of the matter, two-thirds of the troubles which occurred with the protective gear are left unexplained.

While agreeing, therefore, that protective gear requires proper maintenance, I think it is likely that a high percentage of the troubles recorded is due to the design of the protective gear, and the lack of co-ordination of all the component parts.

Protective gear starts at the primary terminals of the current and/or voltage transformers and ends at the tripping terminals of the relay. There is, in my view, far too much concentration upon the relay instead of on

the protective system as a whole. A good deal of trouble and maintenance work on site might be avoided if engineers would specify, when tendering and ordering, a definite rating for the protective gear as a unit; and of course the gear should be tested to make sure that it gives the performance expected of it.

I cannot associate myself with the author's view on the question of assessing the percentage efficiency, because he has apparently left out of the total number of operating occasions the vast number of cases when the conditions were such that the protective gear might have tripped incorrectly, but in actual fact did not do so. I do not see how anyone can correctly assess a percentage efficiently for protective gear, but it is very valuable to have full data recorded in connection with such operations as are known to have occurred.

I agree with the author regarding the provision of test links. These are convenient for routine testing, on site, but in several types of protection, particularly restricted earth leakage, an increased length of lead between transformers is involved where there is any considerable distance between the transformers and the panels on which the test links are mounted. The additional burden imposed by these longer leads is sometimes a serious limitation of the performance.

In Item (*k*)(i) of his comments on Table 5 the author states "Three-phase busbar fault in transformer house supposed to have insufficient earth current to operate leakage protection." I should like to know whether the protective gear was supposed to be sensitive to phase fault as well as to earth fault, because if not, it will be unfair to class that item as a failure of the protective gear as such; although it might be classed as failure to specify adequately the performance that is required of the gear.

Mr. J. F. Shipley: As Adelaide is a district which is occasionally troubled by dust, I am surprised that the paper does not mention instances where dust has caused incorrect operation of relays. Unless a meter case is hermetically sealed it will not be dustproof. The only way to ensure dustproofness is to insulate the outside of the single meter case with a layer of air; in other words, to surround it by a second case.

A recent instance which came to my notice in London was concerned with G.P.O. telephone-type relays used for a very large installation of lifts. The service was such that it involved over 15 000 000 journeys a year, and during the first 2 years there was 1 fault in every 9 000 journeys. An independent engineer who was called in exonerated the manufacturer and diagnosed the faults as being entirely due to dust. He had noticed that the concrete floor was bare, the walls and roof were not painted, and when he walked along the floor a little vortex ring of dust was sent out from his feet. Instructions were therefore given to vacuum-clean the floor, walls and roof of a lift chamber. The floor was then covered with linoleum, which was cemented down with mastic to prevent it acting as a dust bellows, and the walls and roof were sprayed with cellulose paint. A small fan and filter were then installed to supply filtered air under slight excess pressure to prevent the ingress of any atmospheric dust. The result of a 6 months' trial of the modified installation was 1 fault in 68 500 runs, involving about 17 000 000 contact changes, as against 1 fault in about 2 250 000 contact changes with the original arrangement. I believe the G.P.O. standard is 1 fault in about 10 000 000 contact changes.

It seems, therefore, that dust is responsible for a good many more troubles than is sometimes imagined. If I were designing switchgear with relays attached to it I should insist on no relay being placed within 3 ft. of the ground.

Another trouble I have met, but which is not mentioned in the paper because it would not occur in Adelaide, is condensation. This may be responsible for trouble, not only after erection, but during transit. Instrument makers have found the necessity of preventing pieces of apparatus from moving during transit by means of material that is not hygroscopic. In many cases where paper or press-spahn has been used I have found that at the end of a journey of only a fortnight in a ship's hold through the tropics the condensation has ruined not only the contacts but the whole of the interior of the instrument as well. Condensation also causes a deposit (known as "blue mould") on contacts which are not made of platinum, in countries where there are very high humidity conditions for long periods. The consequences of relay or regular contacts being defective may be very serious.

Mr. L. B. S. Golds: With reference to the periodical testing of relays, my experience has inclined me to favour taking the relays off the panel and servicing them in the test room. A large number of relays are installed within 2 ft. of the floor, and it is impossible for a man to service a relay properly when he is lying on the floor. Dust is a much greater source of trouble than has previously been supposed; in my opinion the covers of relays should not be removed in the substation, but there is no objection to doing this where relays are installed in a control room.

It is necessary to test induction relays as far as possible under the circuit conditions in which they are to operate. Under system fault conditions there is considerable impedance in series with the current transformer tending to reduce the proportion of third harmonic in the circuit, but when the relay is tested on a phantom-load test-set the maximum voltage is about 400 volts, and the result is that the impedance of the saturated iron circuit of the relay is a fair proportion of the whole, so that at 15 to 20 times the minimum tripping current on the relay the wave form is far from sinusoidal, and may cause maldiscrimination when relays which may have been tested with the same test set are operating on current transformers of different ratios. This is a point which the author does not sufficiently emphasize.

Relays should be tested at more than 8 times the minimum tripping current, particularly when testing on site, because the effect of the burden of the relay on the current transformer is only beginning to be apparent. The performance of relays with certain current transformers at more than 10 times the minimum tripping current is deplorable. I should like to have more particulars of the characteristics of both the test circuits in the test room and the author's on-site testing transformer. I think that the minimum size of on-site testing transformer which can be used is 5 kVA, and I should like to have the view of the author on this point.

I am glad that he emphasizes the important point that

the relay has only to deal with occasional operations. The pivot and jewel are subjected to tremendous pressures, and in areas where there is heavy traffic I have found that when the relay is taken out of service after 3–4 years in operation there is sometimes a hole bored nearly through the jewel. I would suggest that all jewels used in induction relays should be impact-tested by the manufacturers.

Mr. A. W. Sweetinburgh: I am interested to see that many of the failures listed by the author are really failures of "associated equipment" rather than of relays. I have had similar experience. In looking for the causes of these failures it seems to me that the maintenance tests of the associated equipment should not be ignored. I also think that manufacturers might devote some attention to providing facilities for routine tests.

A good deal has been said by previous speakers about the qualities desirable in a protection engineer; I would point out that many undertakings could not economically include such an individual on their staff, and many of the smaller undertakings who use protective equipment have to be content with hoping that it will function when the occasion arises. This being so, the manufacturers, in their own interests, should try to provide the undertakings with simple means of making tests which will prove that the apparatus, having once been correctly installed, is still in working order. If the arrangement of the associated equipment and the protective gear proper were designed to facilitate such tests, it would be easy for a relatively unskilled man to detect open-circuits, defective insulation, etc.

I have discovered that protective gear which is otherwise perfectly satisfactory does not work very well if a junction box associated with it is soaked with rain water. Another common weakness is that the wiring remote from the control gear but associated with the protective equipment is badly executed. Such defects are not likely to receive the attention of the protection engineer, and the only way to avoid them is by giving more care to the original installation.

Mr. E. S. Bolton (*communicated*): The author states that on his system graded time-delays are avoided wherever possible; I should have thought, however, that it would be better to use them wherever possible, as there are quite a number of instantaneous faults, especially on transmission lines in stormy weather, where if one had a time-lag setting the faults would clear themselves without doing any serious damage. Also, a great amount of time and expense would be saved.

The author does not mention whether he has tested the various types of oil used in circuit-breakers for percentage moisture, inorganic acid, percentage of sludge, etc., over a period of time, and after a fault; nor does he state how often the oil is filtered or changed.

In conclusion, I should like to know whether the author has used the Wedmore type of protection, with two time-lag overload relays and one phase connected for earth fault; and what is his opinion regarding this system of protection.

Mr. A. G. Forgan (*communicated*): The paper deals with a subject the importance of which is often overlooked, particularly by those who fail to realize that the construction of the grid has brought in its train a large increase in the available fault capacity. Not only has the rupturing capacity of switchgear to be increased but steps have to be taken to ensure the reliability of relay operation.

Fig. 4 in the paper shows an excellent design of injection transformer; this diagram would be increased in value if the circuits for and the mechanism of the 120-volt cycle-counter could be added. The importance of an injection test on the primary of a current transformer was shown fairly recently when the manufacturers installed and handed over an oil circuit-breaker with the current-transformer and voltage-transformer leads crossed. Visual examination and operation of the oil circuit-breaker for closing and tripping on control switch and for tripping by closing the relay tripping contacts did not disclose any defect. It remained for a fault to develop, some 6 weeks later, to reveal that the protective system was defective by failing to operate the oil circuit-breaker, thus causing the clearing of the fault to be done by the C.E.B. transformer switches.

The importance of testing the operation of the old-fashioned a.c. trip with time-limit fuses is often overlooked, with the result that the troubles consequent on sluggish operation are not eliminated. These, at the worst, take the form of fusing of cables due to passage of fault current and the firing of oil in the transformers. Testing of current transformers and relays may not, however, reveal incipient insulation breakdowns such as occurred in two cases when the insulation of the primary of a trombone-type current transformer broke down and injected 6·6-kV current into the secondary wiring. This danger should be eliminated with the bar-type primary. It is felt, however, that the pressure of new work in reducing the number of relay inspections must have been beneficial from a cost point of view, without any loss of operational reliability. It should be adequate to carry out annual inspection and testing combined with inspection and testing whenever the operation of the oil circuit-breaker under fault conditions necessitates examination of arcing and main contacts.

Mr. H. J. Fraser (*communicated*): It is desirable that relays and protective equipment should as far as practicable be standardized; though this practice is not necessarily cheap in first cost it should show a saving in ultimate maintenance costs.

Bench tests of relays before installation are valuable, as by this means minor mechanical faults may be detected much more easily than when the relay is mounted in its permanent position. Where the undertaking is a small one and unable to devote special mechanics to this type of testing, a meter testing station is usually available, and routine tests are readily carried out by the meter staff. In view of the large volume of routine testing carried out on the author's system, I presume that a special staff is devoted to this purpose; perhaps he could give some idea as to its constitution, i.e. number of engineers, mechanics, etc.

From Table 2 I note that fuse-shunted trip coils are in use on some of the 7·6-kV radial feeders. Though this forms a very cheap type of protection, in my experience it is most unreliable, as the fuse wire deteriorates rapidly under anything approaching full-load conditions. Also, with heavy fault currents the trip coil may operate

without blowing the fuse, and the circuit may be interrupted at the wrong point.

The author mentions that besides being bench-tested relays are tested after installation by primary injection, presumably from a point within easy reach of the protective current-transformers. Where practicable, does he carry out such tests by injecting current directly into the feeders? It is sometimes possible to isolate a feeder on its own busbar at the generating station, and, where the generator units are not too large, to run up a machine specially for the purpose of testing with simulated faults on the feeder. This gives what is probably the closest approximation to actual fault conditions, but is often difficult to carry out unless the feeder happens to terminate at a generating point.

However, as it is nowadays appreciated that routine testing is important, there appears to be some scope for low-voltage testing equipment of the induction-regulator type, for direct injection current testing on important trunk feeders.

Mr. G. O. McLean (*communicated*): The author's relay maintenance procedure has one or two features which are here considered bad practice. In this category I would place (*a*) the use of single-core 1/14 S.W.G. cable (page 486) on any protective gear; (*b*) the avoidance of test links, especially where routine testing is as frequent as at 4-monthly intervals; and (*c*) the use of "trip-circuit fuses" (page 488).

The author uses a cycle-counter, though most relay times are measured in seconds, and condemns stop-watch methods. Stop-watches (whether spring or synchronously driven) can be started and stopped automatically by the main testing switch. Relay times are greatly affected by the wave form of the test supply, and the paper would have been improved by the inclusion of a complete specification of the author's testing transformer, shown in Fig. 4. Many of the incorrect operations appear to have been caused by vibration, and "an inadequate margin of contact separation" is mentioned (page 492) without any definition in physical terms of "adequacy." For "low inertia" relays in substations near heavy road traffic, I have found $\frac{1}{4}$ in. to be a safe minimum clearance.

Mr. A. E. Quenzer (*communicated*): The paper shows that by overcoming his early difficulties and using the experience gained the author ensures that faulty operations are rarely repeated.

If all relay engineers kept in mind and practised the Conclusions set out on page 494 the approach to 100 % efficiency would not long be delayed.

It is disappointing that the paper makes little mention of insulation tests, either on transformers relays or on wiring. Another point is the omission of remarks concerning relay pivots and bearings.

Referring to Table 5, is there any particular reason for the large difference between the number of operations of the reclose relays during 1937 and 1938? It must be satisfying to the author to note that the percentage of correct operation remains about the same.

Mr. A. E. F. Spence (South Africa) (*communicated*): The author is to be congratulated on the very complete and thorough system of testing and inspection employed on his undertaking. I do not think that every concern of that type could show such a standard—in fact, a sort of cheerful neglect is the lot of many relays and protective systems.

His comments on the various failures are particularly interesting, but it does not seem to be fair to the relays to count all mistakes and carelessness of staff as incorrect operations.

[The author's reply to this discussion will be found on page 503.]

DISCUSSION BEFORE THE NORTH-WESTERN CENTRE, AT MANCHESTER, 23RD JANUARY, 1940, ON THE ABOVE PAPER*

Mr. C. Ryder: The author apparently found relay contacts rather troublesome until the technique of cleaning them correctly had been developed. His photographs show in a very striking manner how easy it is to make the condition of a contact worse by cleaning it in the wrong manner. General experience seems to indicate that, provided alignment is maintained, silver contacts give very little trouble, since a tiny "wipe" is sufficient to break down any moisture film. Once current starts to flow, the arc produced by any attempt to break circuit burns the surface clean, and positive contact is thus established. A tarnished contact surface does not necessarily require cleaning, since the tarnish is mainly silver sulphide, which is practically as good a conductor as the silver. In view of this I should like to ask the author whether under testing conditions the relay contacts actually failed to trip the circuit-breaker or whether they failed to make a test circuit in which the current was limited to a relatively small value; also whether the earlier cleaning operations were responsible for a proportion of later failures.

One of the criticisms made by the author is lack of accessibility for maintenance purposes, but I should like to mention that, in the past, supply authorities themselves have generally insisted on adequate protection against the ingress of dust, etc., when the cover is removed for making adjustments. This feature, however, has been borne in mind in a recent design of relay case in which a removable flat lid is provided for frontal adjustments, such as time and current settings, but for thorough inspection the whole of the case can be removed leaving the relay elements and back-plate attached to the panel.

With regard to Tables 4 and 5, I was expecting to find, from Mr. Bell's remarks in introducing the paper, that relays are responsible for the majority of unnecessary system operations. Table 5 shows, however, that out of a total of 483 operations with 39 incorrect, only 6 incorrect operations were due to the relays themselves. I suggest that the two items "Faulty relay mechanism" and "Faulty relay settings" might with advantage be split up into three, e.g. "Faulty relay," "Faulty maintenance" and "Faulty application."

* The paper by Messrs. J. W. Gallop and R. H. Bousfield, entitled "Applications and Limitations of the Inverse-Time Overload Relay to the Protection of an 11-kV Network" (see page 113), was also read and discussed at this meeting, and the discussion relating to that paper has already been published (see page 129).

This would help to distinguish faulty design, materials or workmanship in the relays from bad handling by the staff for maintenance purposes and the incorrect determination of settings and location of relays. Under these conditions it would seem that the three faults on the 33-kV gear during 1935 which were due to mal-operation of old and obsolete apparatus could be classed as faulty application rather than as faulty relays; perhaps Mr. Brookman would give his views on this point.

Table 4 summarizes the relay operations, the total being 741, of which 724 are correct. With the regrouping suggested above, the incorrect operations would be divided into: 2 due to relays, 10 due to maintenance and application, and 5 due to the human element.

The author is in the best position to assess any relative merits indicated by these figures, since location, service conditions and personnel, all have a bearing on the matter. It would seem, however, from the totals given which indicate a relay operating efficiency of 97·7 %, that the protective relays maintain the high standard so obviously desired by him in his efforts to improve the overall efficiency.

I should have expected the difference between relay operations and system operations to be much greater than is indicated by the figures of 741 and 483 respectively. This, of course, is on the assumption that the totals of relay operations include those relays successfully discriminating together with those "stabilizing" under system fault conditions. Perhaps the author would say whether my assumption is correct, as if so a ratio of, say, 3 or 4 to 1 would normally be anticipated.

Mr. J. E. Peters: I should like to emphasize the importance of making a careful selection of the most suitable protective gear for any given piece of apparatus, always bearing in mind the characteristics of the protective gear on adjacent apparatus, and the need for carrying out thorough inspection and tests after installation, before the protective gear is put into commission. One point should, I think, be added to the author's list of requirements, namely that adequate tests of the complete protective equipment should be carried out in the manufacturer's works to demonstrate its satisfactory performance over the whole range of fault currents to which it may be subjected in practice. This is particularly important where a new design or application is involved, or where stability on through faults depends on the balance of current transformers.

The engineer responsible for testing and commissioning protective gear on site often finds that, with the equipment at his disposal, it is only possible to inject quite a small primary current to confirm that the protective gear has been correctly installed; whereas in the manufacturer's works facilities should exist to test the gear at currents up to the equivalent of maximum fault conditions.

Returning to the question of maintenance, it is rather alarming to note that the author considers it necessary to bring in relays from site every 3 years for bench overhaul and calibration in his test room. Such a procedure has certainly not been found necessary in the N.W. England area of the Central Electricity Board's system, where there are nearly 2 000 protective relays to maintain. Here it is found more convenient to carry out calibration tests on site without disturbing connections, and a relay is only brought in for bench overhaul if it is found to be defective during site tests.

The results of these tests are entered-up on site in a special "technical log," one of which exists for each substation. This technical log is in loose-leaf form and is composed of sheets for recording all the tests and inspections made, each sheet being set out in comparative form. The test engineer has with him, therefore, the complete history of all the protective gear at the substation. For example, if timing tests are being carried out on a relay by secondary injection methods, the appropriate record sheet in the technical log gives also the results of all previous timing tests on that relay together with particulars of any adjustments made; or if insulation-resistance tests are being made on, say, a current-transformer circuit, the corresponding record sheet in the log gives the results of all previous insulation-resistance tests on that circuit. This method of recording tests is found to be most useful and informative, and reduces the time spent on entering-up test records to a minimum.

The author refers to the use of telephone-type relays in connection with his pilot-wire protective schemes; I should be interested to know what maintenance he finds necessary on this type of equipment, what type of pilots are employed and how frequently they are tested.

There are many component parts in a modern protective equipment which require regular attention if the goal of 100 % correct performance is to be attained. Some of the less obvious though vitally important ones are fuses, links, auxiliary switches, multi-core terminal boxes and outdoor current-transformer terminal boxes. I think attention should be drawn to the need for including a periodic inspection and maintenance of these components in any comprehensive maintenance programme.

Mr. S. R. Mellonie: Dealing with the general question of the maintenance of relays, the difficulty does not lie with the relay itself but with the switchgear manufacturers who put the relays in inaccessible positions, e.g. near the floor, where reasonable examination is difficult.

It is desirable to standardize the colouring or mode of flag indication. The manufacturers provide a varied assortment of colours and this leads to confusion when reports are being analysed.

One other point is the testing of the components of the relay connections. There are two circuits—the current-transformer secondary circuit and the trip-coil circuit—and they must be tested separately. The proper way to test a current-transformer secondary circuit is by injecting a current into the primary circuit; but on metalclad gear this presents difficulties.

In my opinion the trip-coil circuit is more liable to faults than the current-transformer secondary circuit. We have adopted a very simple testing device: a 2-pin socket is connected across the relay contacts and the substation inspector carries in his pocket a device consisting of a lamp, current-limiting resistor and 2-pin plug. The combination of lamp and resistor is so arranged that when the device is plugged into a 2-pin socket it passes just sufficient current to light the lamp but not sufficient to trip the oil switch, thereby testing the trip-coil circuit all the way from the battery to the switch and all

the auxiliary connections except the relay contacts. Another device which has proved of great assistance in maintenance work on relays consists of a split plug inserted between the corrugated member of the relay multiplier bridge and the baseplate. The two leads are taken to a suitable supply via an ammeter.

The tests which the author advocates are certainly desirable. For example, loose nuts have been found on current-transformer secondaries, wrong connections, etc., have been discovered, and such defects are by no means confined to the products of obscure firms. Relays are as a rule very inaccessible, the clearances are too small and the marking of the terminal relays is in general inadequate.

Mr. W. H. Diack: In regard to a number of the problems dealt with in the paper the power transmission engineer and the telephone engineer are on common ground. For instance, the author's finding that rounded contacts are the most satisfactory is confirmed by our experience in the Post Office telephone service.

We make a practice of connecting spark-quench circuits across contacts breaking comparatively highly inductive circuits, and of mounting relay springs in the vertical plane to obviate dust deposits as far as possible. The Post Office standard relay uses twin contacts, i.e. two contacts mounted side by side on separate tongues on the same spring. If only one contact is affected by dust the other contact makes the circuit, and it has been found that the act of operating the relay usually has the effect of cleaning the faulty contact. It has been computed that for every 10 faults likely to occur with single contacts not more than 1 is likely to occur with twin contacts.

Other points in regard to which telephone-exchange experience agrees with the author's conclusions are: (1) a steel tool used for cleaning contacts must be clean and nearly smooth; and (2) in normal maintenance, as distinct from overhauls, the contacts should be left alone if no fault or serious wear is apparent. Experiments have been made with benzine and carbon tetrachloride for cleaning contacts. The carbon tetrachloride was found to be the better of the two, but in some cases faults appeared later which were attributed to the building-up of a deposit resulting from the carbon tetrachloride.

I notice that some of the faults mentioned in the paper were due to condensation. There are telephone exchanges in country districts which consist of an enclosed relay group mounted on a telegraph pole and therefore subject to much variation of humidity conditions. Silica gel in a small perforated container is enclosed with the relays and acts successfully as a dehydrating agent.

On page 486 the author makes the statement that inverse time-limit relays are checked and adjusted so that their actual characteristic curves are very close to a common standard for that type rather than to the maker's curve for the particular relay. I take it that this does not refer to the plug and time settings mentioned in the paper by Messrs. Gallop and Bousfield,* but to an alteration which affects the characteristic of the relay. Would not better results be obtained if the maker produced the relay to a specification which included the desired characteristic curve?

Mr. M. Kaufmann: Concerning the author's method of assessing the operating efficiency of protective gear, I suggest that some method ought to be devised which would leave out of account those failures of protective equipment to operate correctly which are directly due to circumstances not connected with the relay or the protective system itself, such as failure of the oil circuit-breaker to clear, or a defective auxiliary switch.

I am sure there are as many ideas of what constitutes efficient maintenance of protective equipment as there are supply undertakings. The difficulties are not so much in framing data sheets and inspection report sheets as in filling them up and keeping them up to date.

I am interested to know whether such a large testing equipment as that shown in Fig. 4, capable of supplying 3 500 amp. to the primary circuits of current transformers, is really portable. Can it be lifted by men on to lorries and wheeled about, or is a block-and-tackle required?

One of the items mentioned in connection with the small testing set of Fig. 7 is the voltage of 0·1 or 0·2 volt for each tapping on the transformer secondary winding. It is stated that the equipment will give up to 15 amp. through the relay coil. If an average value of 5 VA be taken as the relay consumption, 1 volt will be required to give a current of 5 amp., and of course 3 volts to pass 15 amp.; so I am rather puzzled by the figures of 0·1 or 0·2 volt.

Another statement which I think is controversial is that the author would not have links in his protective circuit. I believe that test links or switches are most valuable in protective circuits, and that such circuits will in the future tend more and more to include links.

In comparing protective equipment with telephone and signal relays the author claims a higher percentage of correct operations for the latter; but there is less of what he calls auxiliary equipment in connection with such relays, and since in his analysis he includes failures of all auxiliary equipment the comparison is rather unfair.

Mr. F. Leach: It would be interesting to know whether with the system of fault-recording described in his paper Mr. Brookman found in the case of the Adelaide supply undertaking the same relative figures of performance as are set out in Table 1. I should have expected a generating station with a concentration of plant and skilled labour to have shown the highest performance.

On page 488, 4 months is given as the period for routine inspection and tests; perhaps the author will say whether experiments have been made with more frequent electrical tests and less frequent mechanical inspections, as there is a strong feeling that a relay should not be interfered with, mechanically, unless it is suspected or proved to be faulty. With this in view has consideration been given to the installation in central stations of "routiners" on the lines of those in automatic telephone exchanges? Their use enables frequent electrical tests to be made of the relays, and probably results in improved performance.

I should be glad if the author would give some indication of his experience as to the relative merits of "functional" and "territorial" sub-division of the work of the maintenance staff. Does he find it economical to have an officer, experienced in relay adjustment, to make routine tests and inspections of a number of substations?

* See page 113.

Also, if a relay is found to be faulty, is the procedure to adjust the relay on site, or to fit a reserve relay and bring the faulty piece of apparatus in to a central repair department?

Mr. A. B. Stevenson: I would support the author's view that the E.R.A. basis of assessment of protective efficiency is misleading. His method is much more accurate, but it might be improved if one took as the denominator the product (number of faults) × (number of relays directly involved).

The practice of altering the characteristics of overload relays to suit a standard curve (see page 486) is not to be recommended. It would be much better to buy only one standard type of relay.

The terms "lever setting" and "plunger setting" are not used by British engineers, who prefer "time setting" and "current plug setting."

One major defect in the apparatus shown in Fig. 4 is that the current is entirely dependent on the voltage; this is a serious disadvantage when testing directional relays. Another defect appears to be that when the switch is thrown over from the position shown the cycle counter is subjected to a voltage of almost 240 volts.

On page 492, in his "Comments on Table 4," the author states: "Vibration, set up by men working on switchboard panel, caused pallet switch in a directional relay to make contact." I cannot see how vibration of a panel could cause inadvertent operation, unless at the same time fault conditions existed elsewhere.

Mr. W. H. Lawes: I should like to mention that I have had difficulty in ensuring functioning of latched multi-contact relays. The trouble was due to the use of a fixed steel pin with which the hooked catch engaged. A brass roller of about $\frac{3}{16}$ in. diameter on a phosphor-bronze pin of 0·048 in. diameter was substituted, resulting in definite tripping with a lower volt-ampere consumption and in stability under considerable vibration. The springs for the contacts should be of equal strength and not stubborn, otherwise the drum may not rotate sufficiently to close all the contacts when the number is large.

It is surprising to find german-silver contacts advocated, because nickel alloys are not usually recommended for light contacts. Pure silver is preferable. Abrasives should not be used for cleaning, a very fine-cut file being preferable. Burnishing of the contacts should not be essential, because when the surfaces are roughened after operation the performance of the relay will deteriorate.

Mechanically-tripped indicators, which operate reasonably well when new, may cause errors when any rubbing surfaces become sticky, especially after long periods of inaction. It is also possible for the signal to operate before the contacts have closed. It would be interesting to have the author's views on the reliability of the combined magnetic trip and contact hold-on coil on some relays.

I note that the insulation test of the relay referred to in Fig. 2 is 1 000 volts. Is this the standard value? The English flash test is 2 000 volts, and this voltage discloses incipient troubles due to the use of fibre and other causes.

Has the author any views as to the relative merits of horizontal and vertical discs in induction relays? Horizontal discs show less pivot friction, but collect dust. How effective does he find cover gaskets in preventing ingress of dust? Gaps up to $\frac{1}{16}$ in. have been found between an apparently well-fitting gasket and the cover.

Has the author found that timing errors occur due to the "coasting" of induction relays, i.e. the overswing of the disc after a momentary excess current has dropped to zero? This error is not dealt with in the British Standard Specification for relays. The old relays with fast-moving discs had very little coasting error, and it therefore seems that a high angular velocity is not the cause. Aluminium discs show to advantage in this connection.

It is not possible to obtain proportionate timings at all loads on some types of induction relays. If a relay trips at 30 sec. and 3 sec. respectively at the maximum and minimum ends of the time scale, it may have times of 3 sec. and 0·45 sec. (not 0·3 sec.) at high currents. This may introduce errors due to "crossing" of curves, even with relays of the same type. It would be interesting to know whether any difficulty has arisen from this cause.

Mr. H. B. Dreyfus: The author points out that the settings of the relays on his system are co-ordinated by calculations performed with the assistance of a locally made d.c. calculating table (Fig. 5, Plate 1). Is this calculating table a universal model, or has it been designed to represent the particular system? Also, what accuracy has been found necessary for the resistors used to make up the table?

In his "Comments on Table 3" the author mentions as a minor defect that corrosion was found in the internal connections of a relay. Did this corrosion occur on the d.c. connections? Quite a lot of corrosion of d.c. circuits was originally encountered on the relays and ancillary equipment with which I am associated. This trouble was almost completely overcome by fitting negative biasing equipment which makes the positive terminal of the 110-volt tripping battery about 35 volts negative to earth.

With reference to the section dealing with "Relay Faults," I quite agree with the author about the inaccurate location of some time scales. The inaccuracy can be so great that discrimination is lost between relays in different sections of a system. The only way to check the position, after removing the scale, is to set the scale at zero, and see that the contacts close. This means that every time a scale has been removed in order to examine a relay, either the oil circuit-breaker has to be opened or the tripping has to be disconnected, before one can be sure that the time scale has been put back correctly.

Commenting on "General Maintenance Work," the author has found it necessary to rewind the trip coils of some breakers in order to reduce the tripping current and thus minimize the burning of relay contacts. Has he considered the use of tripping relays having substantial contacts, for making the oil circuit-breaker trip circuits and breaking the relay contact circuits?

Mr. F. Mather: With regard to relay maintenance, I have had no trouble on modern relays except in connection with flag indicators, and on the latest relays even this trouble has been eliminated.

I endorse Mr. Mellonie's remarks about switchgear, as

we also have metalclad gear with bushing-type current transformers where the design makes it almost impossible to carry out primary injection tests.

I am very much in favour of the incorporation of test links in current-transformer secondary and pilot circuits; because otherwise, for testing purposes, one has to be constantly removing the connections from the relays—often a difficult operation.

THE AUTHOR'S REPLY TO THE DISCUSSIONS

Mr. J. R. Brookman (*in reply*): Mr. Lane, who kindly consented to read this paper for me, brings out a number of useful points in his contribution to the discussion, in regard to making adequate provision in the design of switchgear and relay panels to enable the maintenance staff to carry out their work with comfort and safety.

Mr. Lane, Mr. McLeod and Mr. Mather do not agree with me in banning test links from relay circuits, but I can state positively that, with our method of testing, we have experienced little inconvenience arising from their absence, and that if links were desirable in some more complicated protection systems, I would confine their use to such cases, and I would prefer to use the test switch as shown by Mr. Lane in Fig. B.

I agree with Mr. Lane in regard to the value of the simplified key diagram of relay wiring schemes as regards both design and construction, and also in connection with the subsequent maintenance.

Mr. Lane, Mr. Gibbons and Mr. Fraser have referred to the type of men and the training required for the maintenance of a protective system, and with their remarks I am in general agreement. Owing to the rapid growth of the Adelaide Electric Supply Co.'s system and the fact that construction, reconstruction and maintenance are all carried out by the same staff, it is rather difficult to state just what staff is required for maintenance purposes only. The substation superintendent is responsible for the supervision of all this work, and he has an assistant who has specialized in protection. They are both university graduates in engineering, and there are several other graduates or students on the staff. There are two foremen, one of whom carries out the installation and maintenance of the relays, batteries and wiring, while the other deals with circuit-breakers, transformers and substations. Each foreman has several mechanics or fitters under him who have been specially trained for this work. Switchgear and relays usually have to be imported from overseas, and the installation work in connection with them has to be carried out by this department with little assistance from the manufacturers, thus necessitating a larger and more highly qualified staff than would perhaps be justified in an undertaking of similar size in Great Britain.

Mr. Lane, Mr. Wellings, Mr. Spence, Mr. Kaufmann and Mr. Stevenson refer to the formula which I have proposed as a criterion of protection efficiency. My purpose is to provide a method by which the chief engineer, for example, can judge the efficiency as a whole of the relays, wiring, switchgear and staff which have been provided for clearing faults from the system. Obviously, such a formula should have in the numerator the number of protection operations correct according to plan. The denominator must include the total number of protection operations, both correct and incorrect, and also any failures to operate. Mr. Wellings considers that the "vast number of cases" in which relays remain stabilized during a fault should be taken into account, and Mr. Ryder assumes that such relays are included in Table 4. I have taken no account whatever of relays that remain stabilized, as to do so would merely obscure the situation. To include all the back-up relays, for instance, for each operation in Table 4, would merely swamp the significant figures. We have reached the stage where stability of relays under fault conditions is the normal experience, and a failure to discriminate according to plan should be treated as seriously as a failure to operate. False trips are just as liable to cause loss of load as are failures to operate, and, by including them in this way, a satisfactory criterion of protective efficiency is obtained in one formula instead of two as proposed in E.R.A. Report F/T94.

Take, for instance, the figures for generator protection given in Table 2 of the E.R.A. Report, reproduced here as Table A.

Table A

Number of times protective gear has operated ..	44
Correct operations	27
Incorrect operations	17
Failures to operate under fault conditions	4
Actual faults	31

The E.R.A. formulae would give:—

$$\text{Protective efficiency} = (27/31) \times 100 = 87\cdot5\ \%$$
$$\text{Percentage inaccuracy} = (17/31) \times 100 = 55\ \%$$

What is the use of claiming $87\cdot5$ % protective efficiency for systems in which 17 out of 48 trips are false? The application of my formula would award such systems a protective efficiency of $(27/48) \times 100 = 56\cdot5$ %, which puts them in their right class. Again, the application of the E.R.A. formulae to the figures given in the Report for busbar protection (Table 11) shows:—

$$\text{Protective efficiency} = (74/74) \times 100 = 100\ \%$$
$$\text{Percentage inaccuracy} = (8/74) \times 100 = 11\ \%$$

Busbar protective systems in which 8 trips out of 74 are false should not be regarded as having a protective efficiency of 100 %. Applying my proposed formula, the protective efficiency would be $(74/82) \times 100 = 90$ %, which gives a reasonable valuation of the performance of the busbar protection.

Mr. Lane has misunderstood me as proposing that individual relay operations should be taken as the criterion of efficiency. That is the basis of Table 4, but in Table 5 I have taken as the basis the number of occasions on which relays have operated. If Mr. Lane will refer to the section "Methods of Analysis" he will see that this is the case.

The inclusion of inadvertent tripping by the maintenance staff as a cause of reduction of protective efficiency has also been criticized by several commentators, but I contend that the maintenance men are a part of the protective system. If they are unsuitable

men, or poorly trained, the errors they make should be shown. On the other hand, if relays are installed in unsuitable places or are badly designed from a maintenance point of view or if the protective system is excessively complicated, the errors which the maintenance men are bound to make under such conditions should be also shown. Mr. Wellings and others suggest that failures of switchgear to clear faults should not be included as deductions from protective efficiency. The only failures of switchgear which I would not include are those due to inadequate rupturing capacity or breakdown of the major insulation, these being outside the scope of the subject we are considering. Faults in batteries, wiring contactors or trip coils, or in the auxiliary switches, latching and operating mechanism of oil circuit-breakers which cause failure to clear, should be included if we are to have a satisfactory index of the performance of the protective equipment.

I agree with Mr. Wellings, Mr. Sweetinburgh and Mr. Peters, who think that too much emphasis can be laid on relay performance, whereas the associated equipment is equally important and liable to many operating troubles. The auxiliary switches, for instance, of oil circuit-breakers produced by reputable makers are often of poor design, resulting in uncertain action and fouling of contacts by dust. In such important accessories, absence of backlash, provision for fine setting of contacts, wide range of adjustment, substantial contacts, accessibility for cleaning contacts, and enclosure against dust, are essential.

Mr. Wellings discusses the 1938 figures in Table 5; if he will look again at the "Comments" he will see that his remarks were wrongly based, as none of the operations is unexplained.

The opening remarks in my paper, criticized by Mr. Wellings, referred to the relay performance disclosed in E.R.A. Report F/T94, and not to those in Table 5.

With regard to Item k (i) in the "Comments on Table 5," the protection in this case was designed to operate on earth leakage only, with no provision for phase-to-phase protection. The breakdown occurred on isolating switches mounted indoors on a wall, and it is difficult to see how a fault could start, except as a fault to earth. The cause of the flashover has not been ascertained, and may have been a surge. Probably this operation would be better classed as "doubtful" rather than "incorrect." The other points raised by Mr. Wellings have been dealt with in reply to other speakers.

Mr. Shipley, Mr. Golds and Mr. Lawes refer to dust troubles with relay contacts. Particular care is taken to make relay cases dust-tight, and the frequent maintenance schedule prevents trouble. In many cases, contacts are split or duplicated, both in relays and on auxiliary switches of oil circuit-breakers. The advantage of this practice is emphasized by Mr. Diack.

Mr. Golds, Mr. McLean and Mr. Kaufmann raise the question of the wave form of our testing transformers. The wave shape of the large portable testing transformer is by no means perfect, but for many years we encountered no particular difficulty on this account, probably because the errors were of the same order and direction for all the induction-type relays. When, however, a new test bench, having a pure sine wave, was installed, about the time this paper was being written, the difference in relay time due to wave shape became evident. Our present practice is to calibrate all relays with their associated current transformers on the test bench before installation, and settings are thereafter made according to their curves. The transformer is still used for field tests. The small transformer is used only at pick-up values for contact maintenance and to detect friction.

Mr. Lane and Mr. Forgan consider that relay tests once per annum are sufficient. This is corroborated by a recent survey of relay maintenance practice,* although an almost equal number of undertakings reported in favour of maintenance twice per annum. On the other hand, Mr. Lane requires tests of relay wiring each month, whereas I would be satisfied with two or three times a year. An inspection of Table 3 shows 18 minor faults and 3 major faults detected in relay current-transformer and trip circuits in 4 years. Of the major faults, two were in trip coils and one in a relay resistor, so that none was in the wiring itself. I now suggest that a satisfactory maintenance schedule would be, at half-yearly intervals:—

(1) Secondary injection test at slightly over pick-up current to close contacts and trip oil circuit-breaker.

(2) Repeat with oil circuit-breaker open, using 3-volt battery test for contact condition as indicated in Fig. 7.

(3) Test wiring for insulation and continuity. (These tests to be made at 6-monthly intervals.)

(4) Once a year, after making Test (1), remove cover and thoroughly clean and inspect relay. Replace cover and make Test (2).

Mr. Bolton suggests that the use of time-delay relays would permit some faults to clear themselves. My experience is that faults do not clear themselves, but this may be due to the size of the generating plant and the fact that the system neutrals are solidly earthed. Our aim is to remove faults from the system in the shortest possible time.

Oil in circuit-breakers is tested annually for electric strength. Tests for acidity and sludge are made only when considered necessary. We have not made much use of the Wedmore protective scheme described by Mr. Bolton, but so far as it has been used it has been satisfactory.

Mr. Forgan inquires about the mechanism of the cycle-counter: this instrument is supplied by one of the large American manufacturers and is in the nature of an electrically operated escapement.

Mr. Fraser and Mr. Forgan refer to the use of fuse-shunted trip coils. These have proved eminently satisfactory. Cases of high contact resistance, causing the trip coil to operate incorrectly, have occurred only twice in the 4-year period reviewed, and the number of breakers so protected is well over 100.

The shunt fuses are always of ample capacity, as they are used only as short-circuit protection. Either silver or tin alloy fuses are used, mounted in glass tubes, fitted with substantial contacts.

The primary injection tests referred to by Mr. Fraser are made by attaching leads to the conductors adjacent to the current transformers. In the case of metalclad

* *Transactions of the American I.E.E.*, 1939, **58**, p. 206.

gear, the tests are made before the chambers are closed. With pilot-wire protection, power transformers are used to pass the necessary current at low voltage through the main cables, and various types of fault are simulated. These, of course, are installation tests. Subsequent tests are of a secondary injection type.

Mr. McLean disagrees with the use of 1/14 S.W.G. cable on protective gear; we have found it quite satisfactory for panel wiring. Stranded wire is used for the rest of the circuits. He also condemns the use of trip-circuit fuses. Without them, there is the risk of a discharged battery and burnt-out wiring. With them, there is the risk of bad contact in the trip-circuit fuse, or of the fuse being blown and not noticed, or of the fuse being inadvertently left out after testing. For the first of the latter, the remedy lies in the choice of a substantial fuse fitting. For the second, we have an alarm system which calls the control room when any current is drawn from a sub-station battery, as, for instance, by the tripping of an oil circuit-breaker. This alarm would function if a fault on a trip circuit caused one of the fuses to blow. For the third, a partial remedy is a well-trained staff. Under these circumstances, we have arrived at the conclusion that it is better to use trip-circuit fuses. Mr. McLean is apparently using much longer time settings than we are prepared to employ. The great majority of our time-delay relays are set to operate in less than 1½ sec. under short-circuit conditions, and only in rare cases do we use 2 sec. In any case, we find a great variety of uses for the cycle-counter for measuring times down to 2 or 3 cycles. It is electrically started and stopped, thus eliminating the personal factor.

Mr. Quenzer emphasizes the importance of insulation tests. As stated in the paper under the heading " General Maintenance Work," these are made every 4 months. The results are shown in Table 3. We have had relatively little trouble with jewels and pivots. One make of directional relay was mentioned in the paper as giving trouble in this respect (Make B, page 491).

The larger number of operations of reclose relays in 1938 compared with 1937 is due to the greater number of breakers fitted with reclosing mechanism. The percentage of correct operations for these two years is not regarded as satisfactory, but in 1939 the figure improved to 95 %, and it is hoped that further progress will be made. The percentage correct, of course, refers to protection operations only. The percentage of successful reclosures is another matter and is usually about 60 %.

Mr. Ryder asks for information regarding our contact troubles. Reference to Table 3 shows 2 major and 12 minor defects in 1935. The major defects are those in which the contacts failed to pass tripping current when connected to their normal battery. The minor defects are mainly cases where they failed to pass current from a small low-voltage test battery. I believe that most of these cases were due to improper treatment of these contacts at the previous maintenance inspection.

Mr. Ryder suggests further sub-division of the causes of incorrect operation. I agree that his proposed classifications would be informative, provided that the same meanings were attached to them by all the various people using them. I suggest that " design " and " manufacture " refer to the relay as an instrument only and its ability to stand up to the manufacturers' claims in respect of it, and to withstand normal usage. " Maintenance " should, I think, include relay settings. Wrong settings may be due either to the miscalculation or to the mistake of the operator making the adjustment, but they are in the nature of routine. The classification " faulty application " is a difficulty. It often happens that a protection scheme is put in which has certain known defects. It may overlap the field of other relays, or it may have a " blind spot " and reliance is consequently placed on back-up protection. This is usually because a more perfect scheme of protection is either not technically feasible or not economically justified. This should not be classed as wrong application, and as long as the relays operate according to plan the operations should be taken as correct. " Wrong application," however, could apply to relays installed without a due appreciation of the characteristics of either the relays or the current transformers themselves, or of the system which they protect. The former should be known from information supplied by the manufacturer and from bench tests by the user, but the latter is a changeable quantity which occasionally presents us with unexpected situations in which the protection system fails to protect. The application of some relays which may have been correct when first installed may become incorrect on account of system developments. It would appear, therefore, that " wrong application " calls for rather careful definition if general agreement is to be obtained. I would suggest the following sub-divisions:—

(1) Relay faults.
- (a) Design.
- (b) Manufacture.
- (c) Application.
- (d) Maintenance.

(2) Switchgear faults.*
- (a) Design.
- (b) Manufacture.
- (c) Maintenance.

(3) Control wiring and battery faults.
- (a) Design.
- (b) Installation.
- (c) Maintenance.

(4) Human element.

(5) Other causes.

(6) Cause not found.

The telephone-type relays referred to by Mr. Peters are maintained with the same frequency as the other relays. No trouble has been experienced with them. The pilots used are multi-core telephone-type paper-insulated cables with 20-lb. conductors. Mr. Diack mentions the practice of connecting spark-quench circuits across contacts of relays. This should not be necessary in protection relaying, as the circuits are not usually opened by the relay contacts but by an auxiliary switch on the device operated by the relay.

Mr. Diack suggests that, if required, the relay manufacturers would supply relays with characteristics to comply with our specification. It is more economical,

* Excluding failure in rupturing capacity or major insulation.

however, to order standard relays, and make the simple adjustments necessary on the test bench, when making the acceptance test.

Mr. Kaufmann inquires as to the portability of the large testing transformer. This transformer is readily lifted by two men. I am indebted to Mr. Kaufmann for pointing out a mistake in Fig. 7; this has been corrected for the *Journal.*

Mr. Leach inquires about the performance of our generating-station protection relative to that of the rest of the system, suggesting that it should be better on account of the skilled staff available. In Adelaide, however, the power-station relays are maintained by the same staff as that which maintains the rest of the system relays. There have been few faults on generators at the power station, and the operation of feeder circuit-breakers at the power station has been included in the Tables given in the paper. The frequent use of "routiners," as suggested by Mr. Leach, is hardly practicable with protective relays, owing to the interference it would cause with the transmission system, although our 4-monthly inspection is now little more than an electrical test with very little mechanical interference with the relay.

We have found that "functional" rather than "territorial" sub-division of the relay and switchgear maintenance staff is essential on account of the specialized and comparatively infrequent attention necessary at any given location. Faulty relays are adjusted in situ, provided the work can be done conveniently and satisfactorily.

Mr. Stevenson does not approve of adjusting relays to a standard curve, and advises purchasing only one make of relay. This, however, does not answer, as the relays frequently differ from the makers' own curve, and a new batch of relays will differ from the previous ones received.

I note that Mr. Stevenson does not like our terms "lever setting" and "plunger setting." The latter refers to the setting of the plunger of a plunger-type relay. The former is in line with American practice, and the same applies to "tap setting" as against the British engineers' "plug setting."

Mr. Stevenson points out that the current from the testing transformer varies with the applied voltage, and implies that this feature makes it unsuitable for testing directional relays. As tests are usually made at short-circuit values where the relay curves are rather flat, such small variations are not noticeable and the transformer is quite satisfactory for field work. The voltage impressed on the cycle-counter is 120 volts in either position of the switch. The reference to the operation caused by vibration relates to a case in which the time setting of the relay was so short that the trip contacts were separated by only a small gap, and vibration caused them to touch, thus completing the trip circuit, the directional contacts being already closed in consequence of power flow. Apparently Mr. McLean has had a similar experience.

I am in agreement with Mr. Lawes's comments o the advantage of rollers for relay latches of the type mentioned. We have fitted duplicate springs to ensure that the drum can be relied upon to function completely. With regard to the use of nickel-silver contacts, these are used for spring contacts with fairly heavy pressure as in drum-type relays, because it was found that, with two silver contacts rubbing on one another under pressure, there was a tendency to drag the surface and roughen it. When one silver and one nickel-silver contact is used, this does not occur. As mentioned in the paper under the heading "Relay Faults," I am not in favour of flag indicators mechanically operated from the disc, but have had satisfaction from what Mr. Lawes describes as the "magnetic trip and hold-on" type. The voltage test mentioned in Fig. 2 is a test with a 1 000-volt insulation tester. In the test room, the 2 000-volt a.c. test is used. I have had no experience with relays having vertical discs, but do not think the dust problem serious enough to outweigh the advantages of horizontal discs. With reasonable care and attention to the cover gaskets, dust is not a problem in ordinary situations.

The "overswing" of relays, mentioned by Mr. Lawes, is often underestimated. Recent tests which I had carried out showed that back-up relays of the induction type continued rotating after the fault was cut off, for as long as 0·5 sec. The correction to be applied to the time setting of the relay to compensate for overswing is some smaller amount varying from 0·18 sec. for short-circuits of about 5 times plug setting, and a short time setting, to 0·25 sec. with 14 times plug setting and an operating time of $1\frac{1}{2}$ sec. or more. A relay of the same make, but with an aluminium instead of a copper disc, gave slightly lower values of 0·15 and 0·22 sec.

The modern high-speed circuit-breakers mentioned by Mr. Stevenson require about 0·1 sec. to clear a fault, and with a relay having a light aluminium disc with an equivalent overswing time of 0·2 sec. and a safety margin of 0·1 sec. we can use a discrimination time of 0·4 sec. between relays. Few systems, however, are fully equipped with such high-speed breakers, and operating times of 0·15 sec. are more common. With a copper-disc relay having an equivalent time of 0·25 sec. we then have a discriminating time of 0·5 sec., as commonly used.

Replying to Mr. Dreyfus, the calculating table mentioned is a universal type, and the resistors have an accuracy of $\frac{1}{2}$%. Manganin wire is used to minimize temperature error. The difficulty with relay time scales has been overcome in our case by using countersunk-head screws, so that they are self-centring in the holes of the plate. The suggested use of an auxiliary relay is not regarded favourably. Rewinding of trip coils is inexpensive, but it should not be necessary. Switchgear manufacturers could well give their designs more consideration.

In conclusion, I would refer again to the proposed formula for protection efficiency. I believe that considerable benefits would result from the collection and periodical publication of returns from various undertakings, giving their protection efficiency on this basis, and thus directing attention to the subject and stimulating interest in it, much as the publication of thermal efficiencies has done in the field of power-station engineering.

A METHOD OF MEASURING AND RECORDING THE FREQUENCY ERROR OF ALTERNATING-CURRENT POWER SUPPLIES *

By F. O. MORRELL, B.Sc., Associate Member,† and G. R. OMAN, B.Sc.

(*Paper first received 20th January, and in revised form 10th February*, 1940; *read before the* METER AND INSTRUMENT SECTION 1*st March*, 1940.)

SUMMARY

After referring briefly to various methods of measuring frequency, the paper describes in detail an instrument designed to give a statistical record of the inaccuracy in the frequency of a.c. mains supply.

Records have been made, in the Dollis Hill Research Laboratories of the G.P.O., of the mains-frequency error at various times during 1937–40, and statistical analysis of the results obtained in four test periods shows that the distribution follows very closely the normal-error law. The standard deviation of the corresponding normal-error curve has been calculated for each of the test periods.

The purpose for which the recorder was designed was to test the practicability of using a.c. mains supply to drive synchronous motors on teleprinters and multi-frequency generators used in the Post Office telegraph service; the test results are discussed from this standpoint.

(1) INTRODUCTION

With a view to facilitating the synchronization of machines and systems, and also in order to provide a better service to consumers, most electrical power supply authorities have installed frequency-controlling apparatus by which the supply frequency can be maintained very close to the declared figure. The methods of control employed vary somewhat in detail but all are based on the same general principles, which briefly are as follows.

A high-grade clock is fitted with an additional seconds hand, operated from a synchronous motor connected to the supply which is to be controlled. The gearing between the motor and the additional seconds hand is such that if the frequency is correct the hand makes one revolution in a minute, rotating at the same speed as the normal seconds hand of the clock. If, however, the supply frequency is incorrect then one hand either gains or loses on the other and a cumulative phase error results. Either a manual control may be employed, in which case the power-station attendant observing the clock corrects the governors when the error has reached a given amount, or the correction may be applied automatically.

By the use of this system the supply authorities ensure that at least the average frequency is exactly the declared frequency, and variations from the declared frequency have been very much reduced below what was possible previously by the use of simple frequency meters. The consumer can therefore use the mains as a low-grade frequency standard, and synchronous motors can be used for many purposes where constancy of speed is essential.

Probably the best-known application of this characteristic of modern power supply systems is the operation of synchronous clocks, and for this purpose the method of control is very satisfactory, as the difference between true time and synchronous time can be observed directly on the control clock and kept within very small limits. On the London supply network the average error, ignoring the question of sign, is believed to be between 5 and 10 sec., and the maximum error not more than 20 sec. For most other synchronous drives, however, and for frequency-standard purposes, it is the maximum instantaneous frequency error which is of importance, and this is more difficult to assess as the control does not limit directly the instantaneous error. For example, if the load on a network is suddenly reduced owing to, say, the clearing of a faulty feeder which was carrying a large amount of power before the fault developed, the frequency will rise suddenly; but the rise will probably not be corrected until it has caused a certain time error in the control clock. Further, the "severity" of the control is of importance; if a given time error is to be corrected rapidly a greater instantaneous frequency error will be necessary to make the correction than if it is made over a longer period.

The Post Office Engineering Department contemplated the use of synchronous motors for a number of drives, such as teleprinter motors, multi-frequency motor-generators, etc., where a high degree of accuracy of speed is essential, and it was decided to take records of the frequency error on power supply networks to determine whether they would be satisfactory. The recorder described in this paper was developed for this purpose and it is thought that the instrument itself and, more particularly, the results obtained with it, will be of interest to other power users.

(2) PRINCIPLES OF FREQUENCY-ERROR RECORDER DESIGN

There are many ways in which frequency can be measured; the more common arrangements may be classified as shown below.

(*a*) *By counting the number of cycles in a given time.*—This, the most obvious method, has a number of practical disadvantages. An accurate and reliable counting mechanism capable of operating at the mains frequency is required, and very accurate timing of the testing period is necessary.

* The design of the recorder and much of the original work described in this paper are due to Mr. G. R. Oman, who proposed also to prepare a paper on the subject to be read before the Meter and Instrument Section. Unfortunately, in 1938 he had to undergo an operation, from which he did not recover. The paper has been completed by Mr. F. O. Morrell, with whom Mr. Oman was associated at the Post Office Research Station, Dollis Hill.

† Post Office Engineering Department.

(*b*) *Balance or bridge methods.*—These schemes depend on the variation of impedance, and in some cases phase angle, of reactive networks to currents of different frequencies. One of the best-known instruments of this type is the ordinary indicating frequency meter used in power stations. The pointer of this instrument takes up a position dependent on the ratio of currents flowing through an inductor and a condenser connected to the supply mains. A change in frequency causes a change in the current ratio, the impedance of the condenser being inversely proportional and that of the inductor directly proportional to frequency, and alters the position of the pointer. To increase the sensitivity of the instrument resonant circuits may be used instead of simple inductors and condensers. Other arrangements use a.c. bridge networks which are balanced at one frequency only. This type of instrument is affected by wave form and temperature; and while the resulting errors can be reduced to negligible proportions in commercial instruments, these factors would probably lead to difficulties with the order of accuracy required of the present recorder.

An improved frequency meter of this type consists of two networks, one resonant at a frequency above the mean of the instrument, the other resonant at a frequency below the mean; these networks, carrying current from the mains, produce opposing torques on two cam-shaped aluminium discs mounted with the pointer on a common axle. The system moves to a position where the opposing torques are equal. An almost uniform scale can be achieved by suitably shaping the discs, and the accuracy of the instrument is stated to be practically independent of voltage, wave form, and temperature.

(*c*) *Reed-type instruments.*—These comprise a number of tuned reeds, having different natural resonance frequencies, situated in the field of an electromagnet connected to the supply. The reed whose natural frequency is the same as that of the supply vibrates, the vibration being shown by the movement of a small flag attached to the end of the reed. Frequency meters of this type are to be found in the older power stations. They suffer to some extent from temperature errors though not from voltage variations or wave-form distortion.

(*d*) *Comparison with a standard frequency.*—In this method, currents of the frequency to be measured and a standard frequency are passed through a rectifying device, and beats at the difference frequency are counted over a known period of time. This method is used extensively in telephone and radio technique. It is simple and accurate if a reliable standard frequency is available.

In the choice of the type of meter to be used for the investigation in hand, consideration was naturally given to the form in which the results would be the most useful. As will be described in greater detail in Section (4), the main purpose was to test the practicability of using a.c. power mains to drive synchronous motors on teleprinters and multi-frequency generators; hence the maximum frequency error was of the greatest importance, and a figure of 0·75 % has been fixed for the former machines by the C.C.I.T. (Comité Consultatif International Télégraphique). It is not to be expected, however, that the mains error would never exceed this figure, and it was necessary to discover for what fraction of the total time the permissible maximum error is likely to be exceeded. Hence the results are required in statistical form.

Most commercial recorders give a chart record, which is not very suitable for the present instrument, as the analysis of a large number of charts would be an extremely tedious matter and there is no real necessity to know the time when any particular error occurred or whether the error was positive or negative. Mainly for this reason the method described under (*d*) was chosen. Other reasons and advantages were as follows:

(i) As only small variations from the correct value of frequency were to be measured, the method of comparison with a standard frequency was particularly suitable.

(ii) A high-grade standard frequency was conveniently available in the Dollis Hill laboratories in the form of a 1 000-c./s. valve-maintained tuning fork kept at constant temperature and pressure, and used by the Post Office for measuring the frequency of radio transmitters. The accuracy of the fork frequency was known to be better than one part in 10^7, and for the work in hand it could be regarded as an absolute standard.

(iii) A sufficiently high degree of accuracy could easily be obtained without very accurate or expensive components in the recorder itself. Wave-form distortion, voltage variations and temperature changes would not affect the accuracy of the instrument.

(iv) In the design and construction of the recorder, standard telephone components and technique with which the authors were familiar could be used.

The main disadvantage of Method (*d*) is that it is necessary to have a 1 000-cycle supply available wherever it is required to use the recorder. This can nearly always be arranged by using the P.O. telephone network, or, when this is not possible, a portable 1 000-c./s. valve-maintained fork of sufficient accuracy is available.

As the method necessitates the counting of a number of beats it is not possible to make precisely instantaneous readings. It was found that a convenient number of beats could be obtained in a period of 5 or 10 sec., and while slight changes of frequency can be noticed during the counting period they are not large enough to affect seriously the accuracy of the instrument. The maximum errors recorded are thought to be very little below the maximum instantaneous errors, an assumption which is reasonable since it is unlikely that sudden changes in frequency can occur in the large masses rotating synchronously in modern power networks.

(3) DESIGN OF RECORDER

A suitable beat frequency could be obtained by heterodyning the standard-frequency supply with the 20th harmonic of the 50-cycle mains supply. With this arrangement an error of 0·5 %, the maximum anticipated when the recorder was designed, gives 5 beats per sec., and 50 beats could conveniently be counted on a 50-point automatic-telephone type uniselector. The counting period was originally fixed at 10 sec., but later, when errors of more than 0·5 % were being obtained frequently, it was reduced to 5 sec. The accuracy of the instrument is therefore within 0·01 c./s. or 0·02 c./s. respectively, if it is assumed that the duration of the counting period is correct.

A schematic diagram of the recorder is shown in Fig. 1. The mains supply current is passed through a wave-form distorting network, and, with the standard 1 000-cycle supply, is then passed through a narrow-band filter with a mid-band frequency of 1 000 c./s. The two selected frequencies, the standard 1 000 c./s. and the 20th harmonic of the mains frequency, are fed into an anode-bend rectifier, and an impulse relay in the anode circuit operates at the difference or beat frequency. The contacts of this relay operate a telephone-type uniselector, the wipers of which are stepped on once per beat. Additional relay contacts operated by a timing device are arranged to connect the uniselector to the impulse relay for a given period, to disconnect it, make the necessary record and make the selector home automatically under self drive. The bank contacts of the uniselector are paralleled into groups of five, and connected to the electromagnets of ten subscriber's-type meters. A subscriber's meter is essentially an electromagnet with an armature linked up with a "Veeder" counter, so that every time the armature is operated the counter is stepped on one digit.

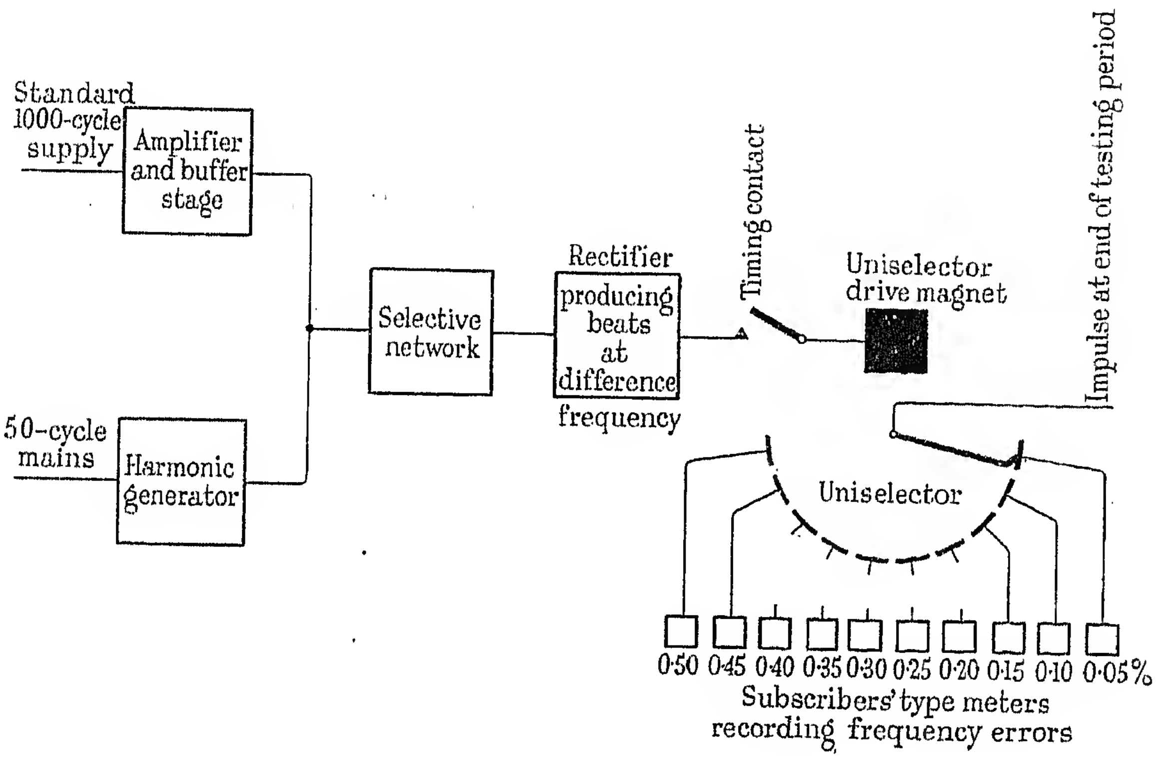


Fig. 1

When the timing relay cuts off the uniselector at the end of a counting period an impulse is transmitted to the wipers and operates the meter connected to the bank contact on which the wipers have come to rest. As five of the uniselector contacts are connected to one meter, each one of the latter covers a small range of frequency error. Thus all errors less than 0·05 % are recorded on meter No. 1, all errors between 0·05 % and 0·10 % on meter No. 2, and so on; the tenth meter covering errors between 0·45 % and 0·50 %. When the measurement has been recorded the selector wipers are automatically reset, and the whole cycle is repeated every 15 sec. By reading the meters at the beginning and end of a test the number of times each error has occurred can be determined.

A complete circuit diagram of the recorder is shown in Fig. 2, and a full description of the circuit is given in the Appendix. The following points in the design are of interest.

(*a*) The wave-form distorting network consists of a bridge-connected copper-oxide rectifier.

(*b*) The narrow-band filter is required to suppress frequencies of 950 c./s. and below and 1 050 c./s. and above, and at the same time to have a fairly constant attenuation at frequencies between 990 and 1 010 c./s.

(*c*) The valve V_3 is included in the standard 1 000-cycle supply circuit to act as a buffer and to give a constant output level. It was anticipated that the level of the standard supply would vary from time to time as it would, possibly, have to be transmitted over long trunk circuits, and it is essential that such variations should not affect the operation of the recorder. A reasonably constant output is obtained by the well-known method of connecting a resistor in the grid circuit, and using a high-ratio input transformer to ensure overloading of the valve with the minimum input likely to be obtained. This also results in the production of a large number of harmonics, which, however, are cut out by the selective network.

If the 1 000-cycle supply should fail, the anode current in the rectifier valve would take up a mean value, and slight variations in this might cause the impulsing relay to operate and release quite independently of the mains frequency. This would result in a large number of false readings. Valve V_3 is therefore normally biased to pass a negligible anode current, and relay D is included in the anode circuit. Hence, when the supply fails, the anode current of V_3 falls, the relay releases and the contact D_1 breaks the counting circuit.

(*d*) As the anode current of valve V_2 is a large proportion of the total anode current it is necessary for the anode supply unit to have good regulation. With this end in view a bridge-connected rectifier is used and the smoothing condensers are connected only on the load side of the smoothing choke.

(*e*) A 50-contact uniselector is used, with the contacts

wired in groups of five to the meters. This was done because it gave a reasonable number of meters and a reasonable counting period, and also because it was not possible to count more accurately than to one beat. For example, if the timing contact opened immediately before the closing of the impulsing contact nothing would be recorded, but if it opened immediately after the closing of the impulsing contact one beat would be recorded. It was necessary, therefore, to have each meter connected to a number of contacts so that an error of one contact would not have serious effect on the results.

(*f*) If an error greater than 0·5 % occurred the uniselector would normally step beyond the 50th contact

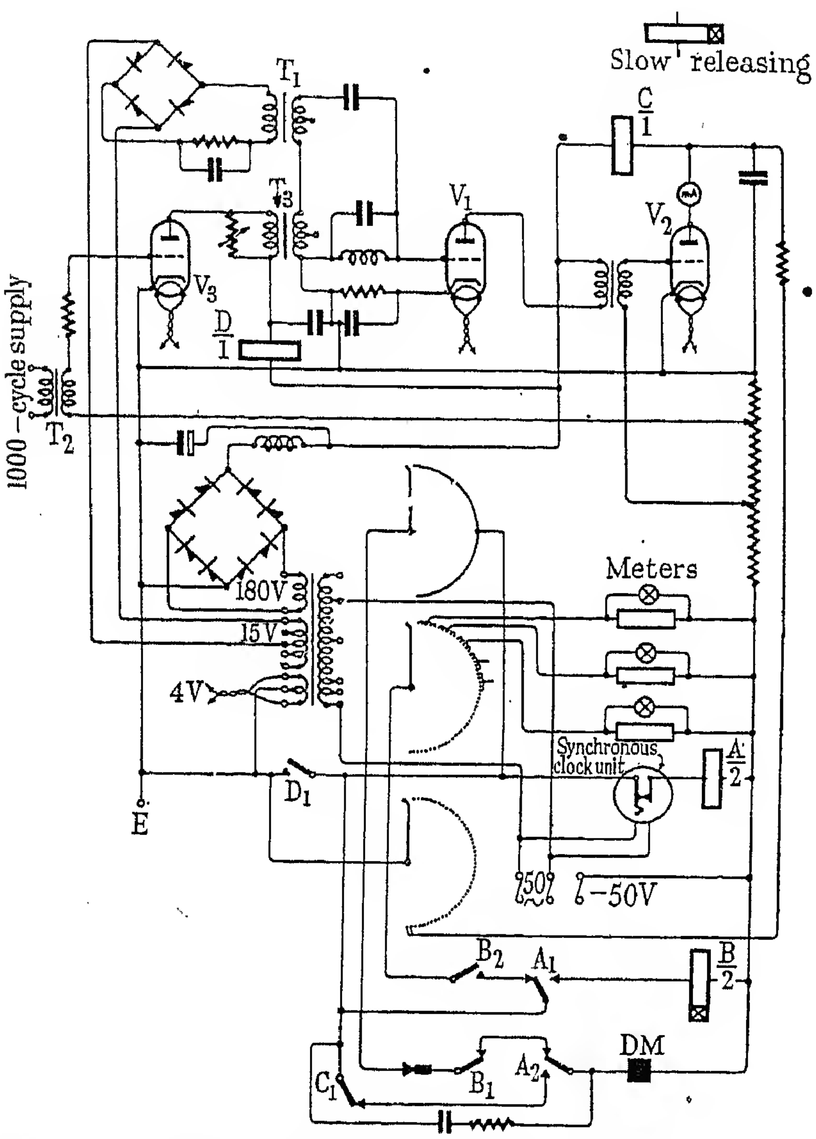


Fig. 2.—Circuit diagram of 50-cycle mains-frequency recorder.

and a low value of error would be recorded. It was preferable for such an error to be recorded as 0·5 %, and to this end the 49th and 50th contacts are connected via a resistor to the anode of V_2. When the wipers step on to these contacts a steady current flows through relay C and further stepping of the uniselector is prevented.

(*g*) The timing of the counting period is controlled by a self-starting synchronous-clock motor which is geared to a shaft making one revolution in 15 sec., and the shaft is fitted with a cam arranged to give a counting period of 10 sec. and a reset period of 5 sec. In later tests made in 1939, when the errors frequently exceeded the range of the instrument, the counting period was reduced to 5 sec. The motor is driven from the supply under test, and errors in the supply frequency cause errors of the same order in the counting period. The effect of this on the accuracy of the instrument can be ignored, however.

(*h*) Although the time at which any particular error occurred was not of primary importance, for the sake of interest a chart record also was kept. The recorder comprises ten pens, situated in line across the paper and controlled by separate electromagnets. Each of the electromagnets is connected in parallel with one of the meters, and a mark, corresponding to the particular meter, is made on the paper whenever a meter is operated.

(4) RESULTS OF TESTS

The recorder has been used for the most part at Dollis Hill, in the Research Laboratories of the Post Office, and has therefore been connected to the South East England section of the grid. For a few days during January,

Table 1

Readings of recorder from 15th April to 20th May, 1937; Monday to Friday 8.0 a.m. to 5.0 p.m., Saturday 8.0 a.m. to 12.30 p.m.

Meter No.	Percentage error	Meter operations	Percentage of total operations	Accumulative percentages
1	Under 0·05	11 352	26·63	26·63
2	0·05–0·10	13 717	32·20	58·83
3	0·10–0·15	9 885	23·17	82·00
4	0·15–0·20	5 070	11·88	93·88
5	0·20–0·25	1 964	4·62	98·50
6	0·25–0·30	373	0·87	99·37
7	0·30–0·35	219	0·517	99·887
8	0·35–0·40	37	0·087	99·974
9	0·40–0·45	9	0·021	99·995
10	Over 0·45	2	0·005	100·000
		42 628		

1939, supply from the South Wales section was transmitted from Cardiff to Dollis Hill over a Cardiff–London voice-frequency telegraph link. The supply was then extended to the recorder over a normal land-line. During these tests it was found that the frequency of the Cardiff supply was always precisely the same as that of the supply in London, showing that the two sections of the grid were running in parallel. It transpired that from December, 1938, most of the grid system had been running as a single unit; hence further tests outside London were unnecessary.

There were four principal testing periods, as follows:

Period No. 1.—From 15th April to 20th May, 1937. Records were taken only during the working day, i.e. 8.0 a.m. to 5.0 p.m., Monday to Friday; 8.0 a.m. to 12.30 p.m., Saturday.

Period No. 2.—From 18th March to 14th April, 1938. Continuous records, 24 hours per day, were taken during this period. Separate records were kept of the readings obtained during the day, night and week-ends.

Period No. 3.—From 12th to 20th January, 1939. During this period nearly all sections of the grid system were running in parallel.

Period No. 4.—January to February, 1940.

The results for period No. 1 are given in Table 1, which shows the number of operations recorded on each meter and the percentage of the total recorded on each meter.

In Fig. 3 the readings are given on a step diagram, which shows, for example, that 26·63 % of the readings were recorded on the first meter, indicating an error of less than 0·05 %, 58·83 % of the readings were recorded on the first two meters, indicating an error of less than 0·10 %, and so on. It was found as a result of statistical analysis that the figures followed closely a normal-error curve of distribution, it being assumed that the average frequency is exactly 50 cycles per sec., and positive and negative errors are equal. The standard deviation of the normal-error curve, i.e. the r.m.s. value of the error, was computed to be 0·114 %, and the curve is shown in the same diagram.

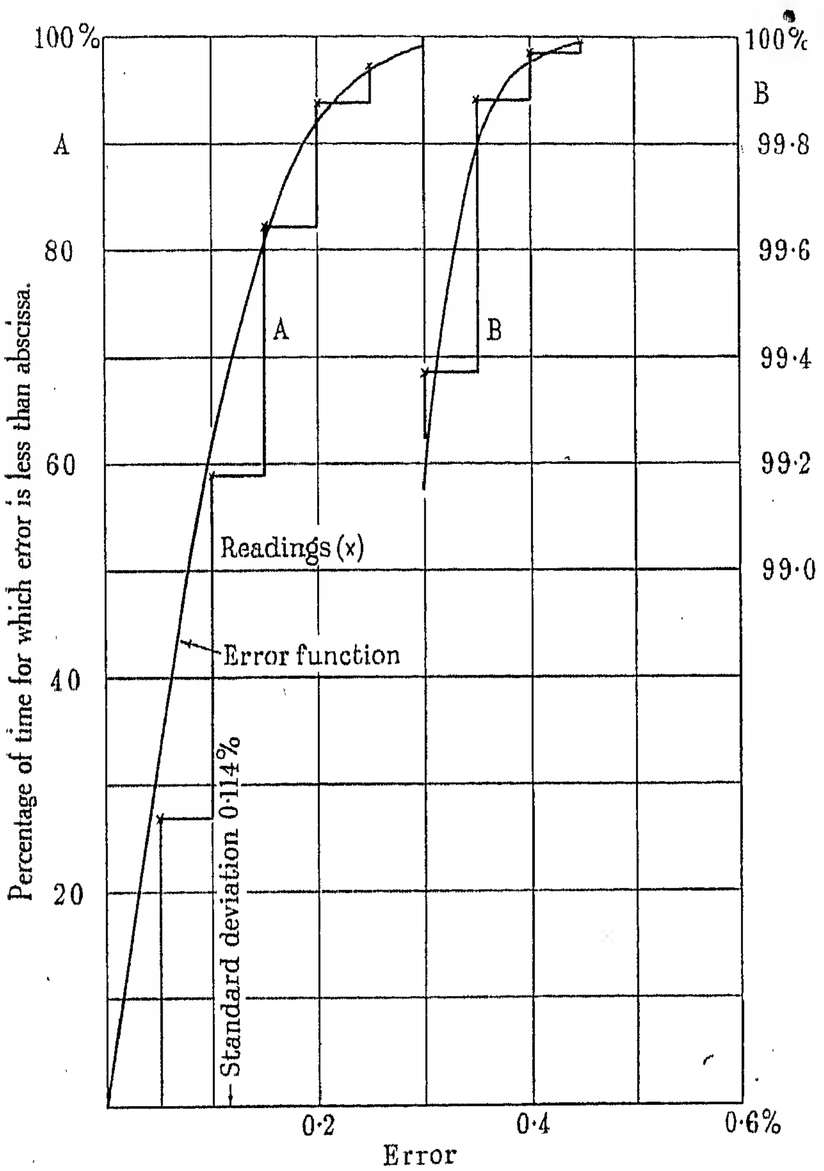


Fig. 3.—Distribution of frequency error: day tests, 15th April to 20th May, 1937.

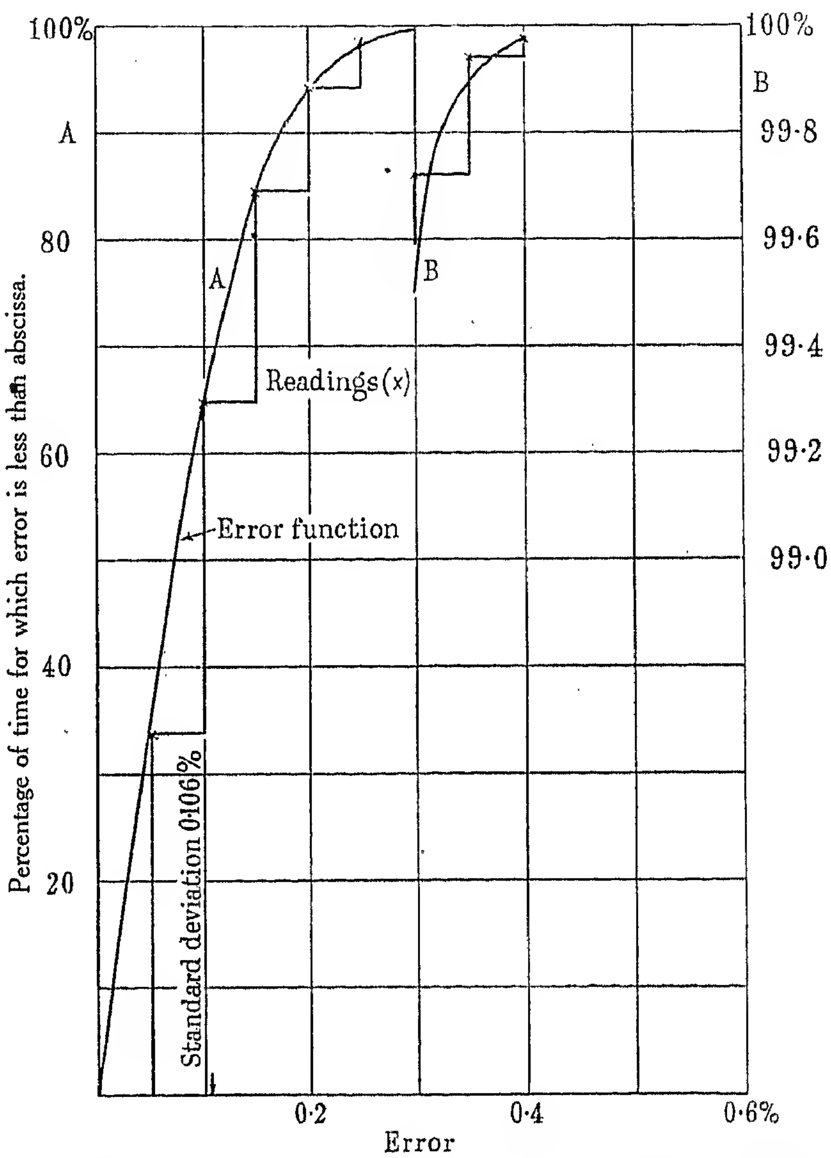


Fig. 4A.—Distribution of frequency error: continuous tests, 18th March to 14th April, 1938.

It is considered that the statistical method of presenting the results is the most satisfactory, for the following reasons.

(i) On account of the method of control and the nature of the problem it is not possible to state that any particular value of error will not be experienced. Any value of error can occur, particularly under abnormal conditions; for example, a complete shutdown can be regarded as an error of 100 %, and any value between this and zero can occur when there are sudden changes of load caused by fault conditions. The most useful way to define the error, therefore, is to quote the proportion of time for which a given error is exceeded or not exceeded.

(ii) For a large number of applications the frequency of large errors which occur comparatively infrequently is of importance. The number of readings of such errors which is obtained in a test lasting even 1 month is small, and it is probable that the value calculated from a normal-error curve, fitting the whole of the results, will be the more accurate.

(iii) The standard deviation of the normal-error curve is a precise figure from which the results of any test can be gauged, and different tests and supply systems compared.

The step diagrams, the probable normal-error distribution curves and the standard deviations are given for the first three periods in Figs. 3 to 5. The normal-error curves are in two parts, the ordinates of the second part, B, being drawn to an enlarged scale to show more clearly the probable frequency of occurrence of large errors.

Figs. 4A, 4B, 4C and 4D cover the second period: Fig. 4A gives the results obtained in tests occupying 24 hours per day; Fig. 4B, the results obtained during the working days, i.e. 8.0 a.m. to 5.0 p.m., Monday to Friday, and 8.0 a.m. to 12.30 p.m. Saturday; Fig. 4C, night readings, 5.0 p.m. to 8.0 a.m., Monday to Friday; and Fig. 4D, week-end readings, 12.30 p.m. Saturday to 8.0 a.m. Monday. As is to be expected, the greatest errors occur during the day when there is maximum change of load, the smallest during the night, and the week-end and continuous readings are intermediate between the other two sets.

Figs. 3 and 4B, both referring to day readings, are directly comparable and show standard deviations of 0·114 % and 0·115 % respectively. This result is particularly interesting when it is remembered that the tests were separated by an interval of nearly 1 year. It is believed that the conditions on the supply system were not altered appreciably between the tests, i.e. throughout both periods the South East England section of the grid was not connected to any other section.

It will be noticed that departures of the readings from the normal-error curve are much greater for both these periods than for the other periods, and in each case the percentage readings of small errors lie below the curve and percentage readings of large errors lie above the curve. The reason for this is not quite clear, though the wider variations of load and frequency experienced during the daytime may be a partial explanation.

Figs. 4A and 5 are also comparable cases, both referring to continuous tests. The standard deviations are 0·106 % and 0·175 % respectively, showing a very large increase, which is, in all probability, due to the fact that when the latter result was obtained, practically the whole of the grid system was running as a single unit. It will be noticed also that the agreement between the readings and the normal-error curve is extremely good even though the testing period was only 9 days.

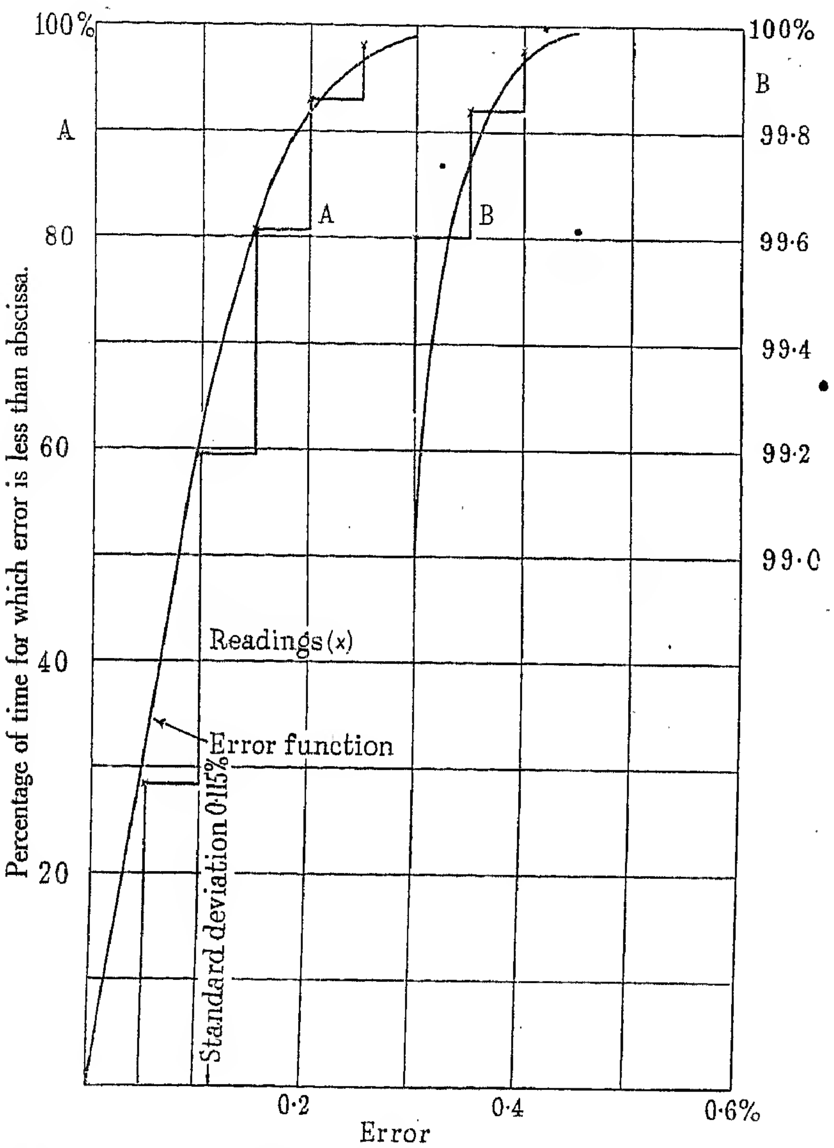


Fig. 4B.—Distribution of frequency error: day tests, 18th March to 14th April, 1938.

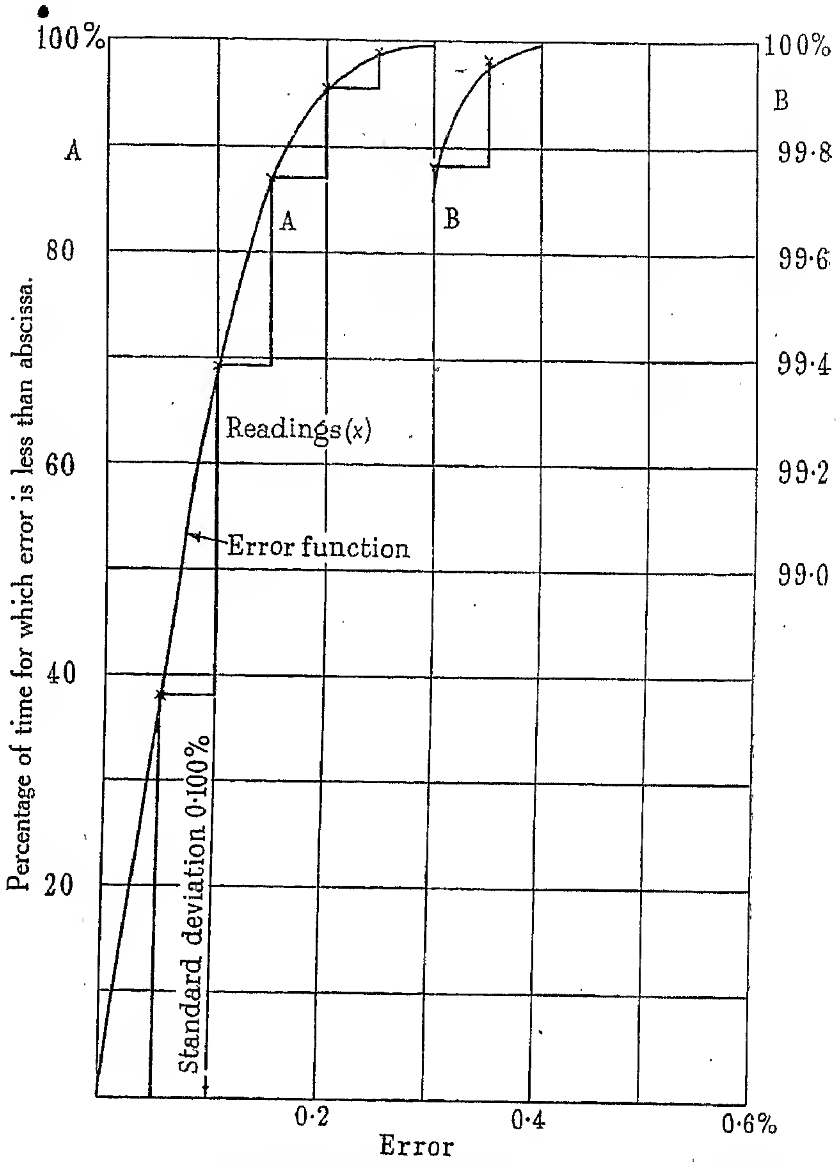


Fig. 4C.—Distribution of frequency error: night tests, 18th March to 14th April, 1938.

It would appear that on account of the inertia of a large power system minor changes of load would not have an appreciable effect on frequency; nevertheless, at times when the load on all parts of the system is increasing or decreasing, as, for example, in the morning or evening, considerably wider variations of frequency are to be expected. It is believed that the frequency is controlled by one controlling station situated in London, and the following procedure is adopted when a change in frequency is required.

The load to be supplied by the various sections of the system at any particular time can be anticipated fairly closely, and the section controlling stations are therefore instructed to supply load in accordance with the antici-

pated demands. When the load over the whole system is gradually increasing the effect is merely a reduction in frequency, without a substantial change in the proportions of the total load supplied by each section. The frequency-controlling station must therefore initiate the frequency-change by increasing the speed of the generators in the local area, and in consequence the speed of all generators on the system, thereby taking a greater proportion of the total load. The neighbouring sections therefore readjust their machines to supply loads

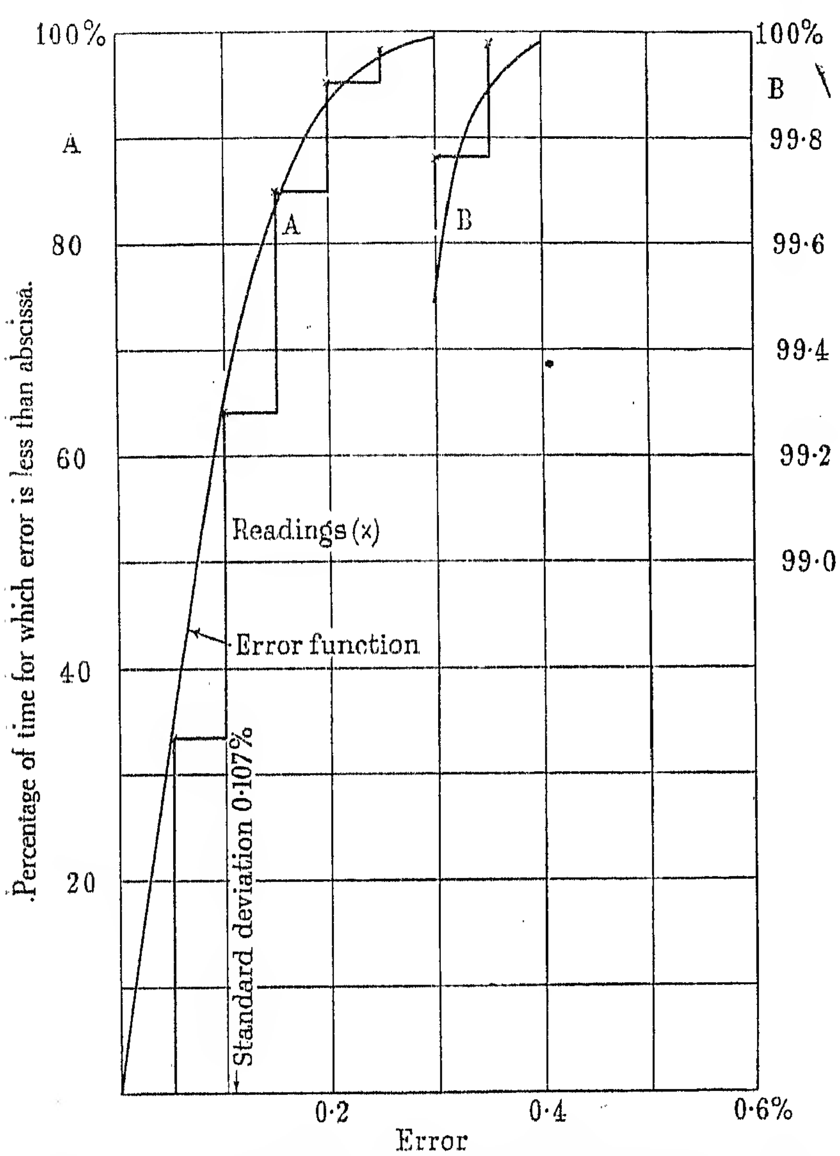


Fig. 4D.—Distribution of frequency error: week-end tests, 18th March to 14th April, 1938.

in accordance with their instructions, and eventually all machines on the system have been readjusted to take the required loads at the increased speed.

The whole process naturally takes some considerable time to perform, and with a rapidly changing total load on the system considerable skill is required to estimate accurately the magnitude of the change of output from the local generators required to bring about the final frequency-change. It would appear that the probable change of load whilst the frequency-change is taking place would need to be known very accurately, and that it would be easy to over-estimate the amount of correction required, in which case the mains frequency would swing to the other side of the nominal value.

It seems likely, therefore, that both the extent of the system and the rate of change of load influence the magnitude of frequency variations, and this is confirmed by meter and chart records.

The standard deviation of frequency errors in January and February, 1940, was 0·23 %, and tests made in March and April show a gradual improvement to 0·19 % obtained at the end of the latter month. All of these were continuous tests.

(5) APPLICATION OF TEST RESULTS

For period No. 3 the results have been rearranged in Table 2 to show the percentage of readings which are greater than given values of error.

As an example of the use of this information, the case

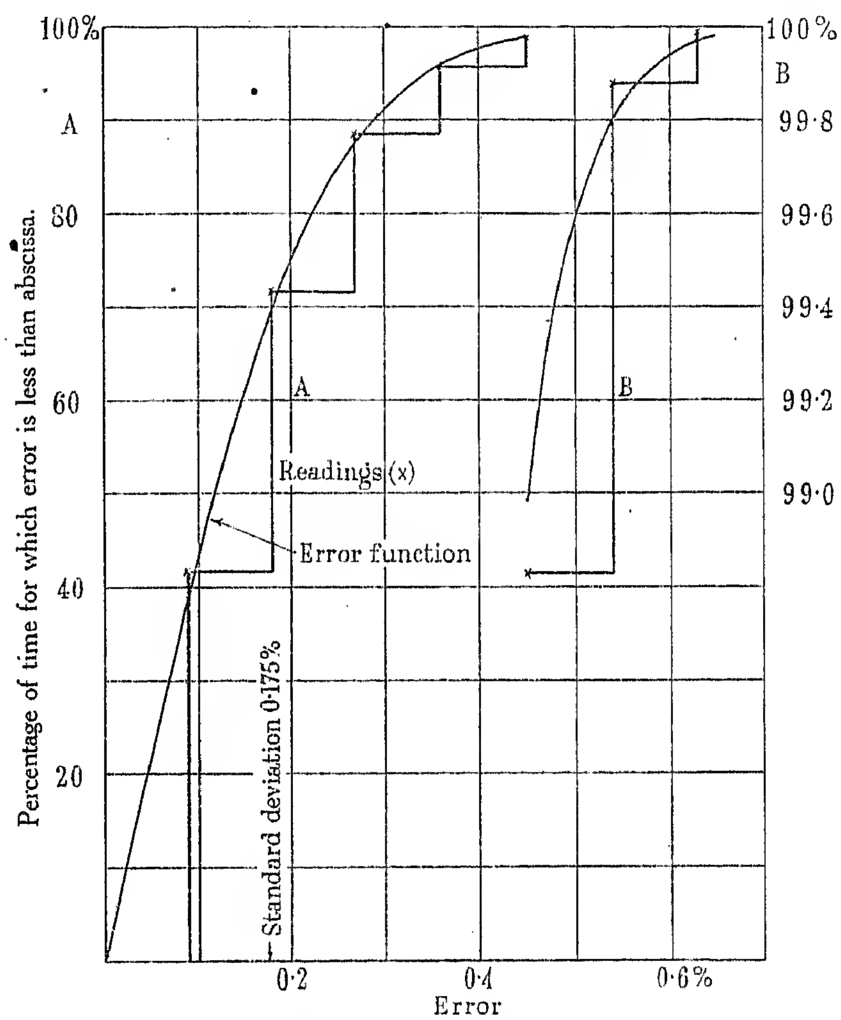


Fig. 5.—Distribution of frequency error: continuous tests, 12th to 20th January, 1939.

of the teleprinter driving motor can be considered. Teleprinters are machine telegraph instruments operating on the start-stop system, that is to say the receiving mechanism is started by means of a clutch, on the receipt of a start signal, at the commencement of each character and stopped at the end of it, the driving motor running continuously the whole time. Cumulative speed errors extending over more than one letter are thus avoided, but for satisfactory operation it is essential that the speed of the machine shall be reasonably accurate. A speed-tolerance figure of $\pm$ 0·75 % has been laid down by the C.C.I.T. for these machines and, up to the present, this has been achieved by means of d.c. motors controlled by an electrical governor operating in the motor field or armature circuits. Dry metal rectifiers have to be used when the supply is alternating current. It will be seen

from Table 2 and the corresponding normal-error curve that the chance of the frequency error exceeding 0·75 % on a 24-hours-per-day measurement is exceedingly small. Reference to appropriate probability tables gives a value of only 0·00184 %, i.e. less than 0·2 minute per week, which is negligible. For 99 % of the time the error will not exceed 0·45 %. A synchronous-motor drive should therefore be quite satisfactory; in fact, it would probably be better than the d.c. governed motor.

There are, naturally, other considerations affecting the adoption of synchronous motors, notably the necessity of providing emergency supplies in large and important centres; but in more normal times it would undoubtedly result in considerable economies.

A second example is that of a multi-frequency motor-generator used on voice-frequency multi-channel telegraph systems. The generator used at present in the Post Office telegraph service consists of a d.c. motor driving 18 small inductor-type alternators mounted on the same shaft. The alternators produce alternating currents of 18 different frequencies ranging from 420 c./s. to 2 460 c./s. in steps of 120 c./s., each frequency being the carrier for one telegraph channel. It is necessary to maintain the carrier frequencies within 0·25 % of the nominal values, and in consequence the same accuracy is required in the speed of the driving motors. Direct-current motors, with contact governors in the field circuit, are used at present, but considerable maintenance is required to maintain the required speed accuracy on what is, otherwise, a simple and reliable machine; and it would be a great advantage if such machines could be driven from the mains. Reference to the curve shows that the permissible limit of 0·25 % is exceeded for more than 15 % of the time; hence the use of the mains for this purpose is not really practicable.

Table 2

TIME FOR WHICH A GIVEN ERROR IS EXCEEDED

Error greater than	Readings		Normal-error curve	
	Percentage	Minutes per week	Percentage	Minutes per week
0·09 %	58·6	5 910	61·02	6 150
0·18 %	28·3	2 860	30·30	3 060
0·27 %	11·5	1 160	12·36	1 245
0·36 %	4·21	425	3·94	398
0·45 %	1·18	119	1·018	103
0·54 %	0·119	12·0	0·208	21·0
0·63 %	0·002	0·2	0·0318	3·21
0·72 %	—	—	0·00396	0·400

(6) ACKNOWLEDGMENTS

Acknowledgments are due to Mr. J. S. Forrest, of the Central Electricity Board; to Mr. G. F. Shotter, of the Northmet Power Co.; and to many others who have assisted in the preparation of this paper. Finally, thanks are due to Col. A. S. Angwin, the Engineer-in-Chief of the Post Office, for permission to publish the information contained in it.

APPENDIX

A circuit diagram of the recorder is given in Fig. 2. It consists of a valve amplifier-rectifier producing the beats, a uniselector relay to count the beats, and a power supply unit. The diagram shows the relays and uniselector operated from a 50-volt d.c. supply, which is usually available in telephone exchanges, but a suitable a.c. unit is also available.

The output from a winding on the mains transformer is passed through the bridge-connected copper-oxide rectifier, the wave-form distorting device, and via the 600-ohm resistor and 2-μF condenser to the transformer T_1. The standard 1 000-cycle supply is fed to the primary winding of transformer T_2, the secondary winding of which is connected to the grid of the valve V_3. Transformer T_3 is connected in the anode circuit of V_3 and shunted by a 10 000-ohm variable resistor as a volume control. The secondary windings of T_1 and T_3 are connected in series, and the combined outputs are fed via the selective network to the amplifying valve V_1, which is followed by an anode-bend rectifier V_2.

Table 3

FREQUENCY ERRORS RECORDED ON METERS

Meter No.	Percentage error	
	Counting period 10 sec.	Counting period 5 sec.
1	<0·05	<0·10
2	0·05–0·10	0·10–0·20
3	0·10–0·15	0·20–0·30
4	0·15–0·20	0·30–0·40
5	0·20–0·25	0·40–0·50
6	0·25–0·30	0·50–0·60
7	0·30–0·35	0·60–0·70
8	0·35–0·40	0·70–0·80
9	0·40–0·45	0·80–0·90
10	>0·45	>0·90

The timing of the counting period is controlled by a self-starting synchronous motor operated from the supply under test. The motor is geared to drive a shaft at a speed of 1 revolution in 15 sec., the shaft being fitted with a cam which closes a pair of contacts for the counting period (10 or 5 sec.) and opens them for the remainder of the 15 sec. (5 or 10 sec.).

When these contacts close, the relay A/2 is operated via the contacts D_1 (which are normally closed) and connects the drive magnet of the uniselector to the contacts C_1 of the relay C/1, via the contacts A_2. At the same time the contacts A_1 close and operate the relay B/2. At the end of the counting period, relay A/2 is released and the uniselector drive circuit is broken at A_2, which also prepares a homing circuit for the uniselector, and an earth is connected by the contacts A_1, via B_2 closed, to the wiper No. 3 and operates the subscriber's meter connected to the bank contact on which the wiper has come to rest. The relay B/2, which is a slow-to-release

relay, then releases (its energizing circuit was broken when relay A released); the meter-operating circuit is broken at B_2; the relay homing circuit is completed at B_1 via the interrupter springs and the homing arc, and the uniselector automatically returns to the first contact. At the end of a 5-sec. rest period the relay A/2 is re-operated and the cycle repeated.

From this description it will be seen that the uniselector counts for a period of 10 or 5 sec. Since the test frequency is 1 000 c./s. there are 10 000 cycles in 10 sec., and an error of one beat in this period is 1 part in 10 000, i.e. 0·01 %. The uniselector has 50 contacts, and these are wired in groups of 5–10 subscribers'-type meters. The meters therefore record errors as shown in Table 3.

If the error was greater than the maximum range of the instrument the uniselector would normally stop beyond the 50th contact, and a reading of a low value would be recorded. As it is preferable that such an error be recorded as the maximum and not as a lower value, contacts Nos. 49 and 50 on Bank 2 of the uniselector are wired via a 10 000-ohm resistor to the anode of the valve V_2. When the uniselector steps on to these contacts, therefore, a steady current flows through relay C/1 via this resistor to earth, and further stepping of the uniselector is prevented.

The relay D and contact D_1 are included in the circuit to cut off the counter mechanism when the standard 1 000-cycle supply fails. The valve V_3 is operated with a grid bias which, in the absence of the supply, reduces the anode current almost to zero. This releases D/1 and opens the contact D_1, which removes the earth from the counting circuit.

The valve anode-supply rectifier is fed from the 180-volt winding on the mains transformer. A bridge-connected copper-oxide rectifier is used, and smoothing is provided by a choke and a 30-μF electrolytic condenser.

[The reading of the paper was followed by a demonstration by Mr. L. Essen of the principles of the Quartz-Crystal Clock.]

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 1ST MARCH, 1940, ON THE ABOVE PAPER BY MESSRS. MORRELL AND OMAN, AND COMMENTS ON THE DEMONSTRATION BY MR. ESSEN

Dr. W. G. Radley: I have been told that the suggestion that the work which has been described should be put on record by means of a paper read before The Institution was originally Mr. Oman's and that, when he was taken into hospital, he took with him the material to enable him, in the anticipated days of his convalescence, to work on the preparation of the first draft of the paper. It is a fitting tribute to his memory that the work which he started should have been rounded off and described by the officer in charge of his research group.

The paper throws open the door to discussion of two questions of rather wider interest than is suggested by its title: firstly, the value of statistical methods in engineering; and secondly, the importance of frequency control of a.c. supplies.

A recent paper by Messrs. Dudding and Jennett* discussed the application of statistical control of quality to the manufacturing industry. In the Post Office, we are used to the idea of controlling quality of service by means of sample tests. One of our principal problems is that of balancing the desire to give a no-delay service against the uneconomic provision of plant which will be but rarely used; we recognize that failures must occur occasionally, but set a limit to the frequency of their occurrence. A somewhat similar problem faced the authors of this paper. They realized that occasionally a.c. supplies would vary to such an extent that teleprinters driven thereby would fail; the problem, therefore, was to determine the frequency with which failure would occur. The statistical method gives this information with accuracy from a minimum number of observations. As a preliminary, we have to determine when the data that we are accumulating are representative of the conditions. (The technique in use at the Post Office Research Station for discovering when one has taken enough measurements is described in a contribution to the discussion on Messrs. Dudding and Jennett's paper, already referred to.) We have then to fit those data to some form of distribution curve. Mr. Morrell suggests that in the present case the readings of frequency fall on the normal-error curve but that there are slight discrepancies in the fit, especially so far as the readings taken during the daytime (Figs. 3 and 4B) are concerned. Is it not likely that the true explanation is that these readings do not fall on one normal-error curve but on two, one with a peak slightly below and the other with a peak slightly above 50 c./s.? An explanation which suggests itself to me is that when the mains-driven clock in the controlling station is fast one aims at a frequency slightly below 50 c./s. so as to overtake the error, and conversely when the clock is slow.

With regard to the importance of accuracy of frequency, with the existing system teleprinters can be driven by a.c. motors if the frequency is stable within $\pm$ 0·75 %; but if all teleprinters were driven from the a.c. supply and the supplies at the transmitting and receiving ends were synchronized we could work with much greater errors than that. In practice, however, the majority of teleprinters are driven by d.c. motors.

The figures given in the paper indicate that since supplies have been synchronized with many, if not all, sections of the grid system running in parallel, frequency errors have been somewhat greater than they were before. I should like to know whether we may expect a further deterioration in the standard.

In the Post Office, we have not many applications for low-grade-accuracy frequency standards. For the majority of our applications, such as control of the frequency of telephone carrier systems or of the wavelength of radio stations, we use a high-grade standard which is accurate to better than 1 part in 10 millions. I would suggest, however, that the authors' instrument might be very usefully employed by the power supply industry. It presents information regarding frequency stability of 50-cycle mains in a form which requires less

* *Journal I.E.E.*, 1940, **87**, p. 1.

sorting-out than is necessary with the type of chart usually associated with a frequency-measuring device.

Mr. J. S. Forrest: Although frequency measurement by beat methods has been commonly employed for audio-frequency and radio-frequency work, I think that this is the first investigation in which this technique has been seriously used for the measurement of commercial power frequencies.

Fifteen years ago, in the days of single power-station systems, it was sufficient if the frequency was known to within 1–2 c./s. Nowadays, however, very large interconnected systems—for example, the national system, with a plant capacity of 6 000 MW—may be controlled from one point, and in such cases a change of frequency of 0·05 c./s. is significant.

Statistical methods of recording frequency variations have not so far been employed on the national system. We have frequency recorders in all control rooms, and a survey of the frequency charts indicates that the diagrams of distribution of frequency errors given in the present paper do give a good picture of the frequency variations. Broadly speaking, the frequency is kept constant to within 0·1 or 0·2 c./s., and variations of more than 0·3 c./s. seldom occur, at least on large interconnected networks. Occasionally larger variations occur on a local system when owing to fault conditions it becomes disconnected from the national network; and in these circumstances there may be for a short period a frequency-change of the order of 1 c./s., the frequency rising if the local station had been exporting, and dropping if it had been importing, before the fault occurred.

We have also installed time-error recorders in all the control rooms, and these instruments give a continuous record of the difference between frequency time and standard time; the remarks on time errors in the Introduction to the paper are confirmed by the records obtained from these recorders.

The slight deterioration which has occurred already in the frequency control was due to the following cause. Until December, 1938, the grid was operated with two or three areas in parallel, and a technique of frequency control had been developed which had reached a fairly high standard. In December, 1938, however, it was found advisable to interconnect all the areas, and to control the complete grid system from one point. Under these conditions, it is inevitable that the control should become less rigorous, unless there is a considerable increase in the supervisory and communication facilities. In the future, owing to the use of more sensitive and refined methods of control, the position should improve.

The method described in the paper is not in general applicable to control purposes, as an indicating instrument is required which will give the instantaneous frequency. The accuracy obtained (0·01 to 0·02 c./s.) is, however, sufficiently high for operation purposes, so that the authors' instrument should have some useful applications in comparing the efficiency of frequency control on different networks and in comparing different methods of control on the same network.

About a year ago, in conjunction with Mr. Morrell, we compared the results obtained at Dollis Hill with those given by our own recorders; perfect agreement was obtained when the frequency was 50 c./s., but when a frequency error was present the Post Office instrument indicated a larger error than did our own recorders. Investigating the matter further, we chose a particular date when we knew that the frequency error was larger than usual, and obtained the recorder readings from Birmingham, Manchester and London. The mean frequency for these three recorders at this time was 49·67 c./s., and the maximum discrepancy between the recorders, which were not all of the same make, was 0·05 c./s. On this occasion, the Dollis Hill instrument gave a reading of 49·5 c./s. Translating these figures into the terms given in this paper, the C.E.B. recorders gave a frequency error of 0·66 % ± 0·05 %, and the Post Office instrument an error of 1 %. At the time we were unable to clear up this discrepancy, and I should be interested to know whether Mr. Morrell has obtained any information since which would throw any light on the matter.

Mr. F. Hope-Jones: If the frequency of the grid supply could be relied upon to remain constant to a greater degree of accuracy than it does at present, the supply mains would be useful in physical laboratories and in wireless and television work: in fact, wherever tests against time are carried out. The mains can give us a chronograph pen record which can be read directly in 100ths of a second. They might also provide the sidereal telescope drive at Greenwich and other observatories.

On looking through the paper I am reminded that in 1899 I myself read a paper* before The Institution on the subject of electric clocks, and that 4 years previously I had forecast in *Lightning* the coming of the synchronous-motor clocks which have since proved so useful.

Up to a few years ago the timekeeping of the grid had been steadily improving, and it had kept within 3 or 4 sec. for long periods. It degenerated about 1938, and we are now told why. Until then, only two or three sections or areas had been run in parallel, but they have all been put in parallel since.

Turning to the demonstration of the quartz-crystal clock, I should be glad if Mr. Essen would tell us something of the necessity of rigorous control of the temperature in which it operates.

As long ago as 1927 Mr. Loomis, an amateur astronomer of Tuxedo Park, 40 miles from New York, acquired three Synchronome Shortt free-pendulum clocks. He mounted them on solid rock faced with concrete, arranged in the form of an equilateral triangle so that one pendulum would not influence another by its beats being transmitted through the support. He also obtained from Mr. James Marrison, whom I have always looked upon as the pioneer of the quartz clock, a service of 1 000 c./s. transmitted on a land-line, being a sub-multiple of the natural frequency (100 000 c./s.) of the ring of quartz in the Bell Telephone laboratories in New York.

Mr. Loomis then invented a spark micro-chronograph which enabled him to compare these two methods of timekeeping. Every half-minute, in the act of receiving their impulses from the Synchronome clocks, the pendulums automatically caused a spark to pierce a band of brown paper 10 in. wide, this paper being made to progress continuously by a phonic wheel in the crystal's

* *Journal I.E.E.*, 1900, **29**, p. 119.

circuit. The measurements went on for 8 months, and then the records were examined by the mathematicians at Harvard, Prof. E. W. Brown and Dr. Brouwer. The mathematical analysis of their rates showed that there was a definite disturbance of one pendulum as a result of the vibrations of the other two, in spite of the precautions above described. They eliminated that, but they still found a persistent residual wave of exactly the lunar period ($10\frac{1}{2}$ hours), which of course represented the small change in the value of gravity due to the alternate addition and subtraction of the effect of the moon. The amplitude of the wave, i.e. the maximum difference in time between the quartz clock and the pendulum clocks, was 0·0002 sec.

It had always been assumed that no clock was capable of sufficient accuracy to perform such a feat. Even when such extraordinary precision of time measurement became available, the lunar period could never have been revealed without something to compare it with which was not based upon gravity. It was a spectacular demonstration of the accuracy of the quartz-crystal clock.

Mr. R. O. Carter: I should like to refer briefly to two applications where the accuracy of the supply frequency is important.

The first is in connection with the use of dry-plate rectifiers for floating secondary-cell batteries in, for example, small unattended exchanges where it is desired to maintain the floating voltage of the battery extremely constant even when the supply voltage and the load vary considerably. This is achieved in most cases by the use of transformers or chokes saturated either by direct current or by alternating current, these being sometimes tuned to the supply frequency or to one of its harmonics. To give the results obtained with a particular set, the combined effect of a 6 % change of supply voltage and a change of load from the minimum to the maximum for which the set was designed (in the more adverse direction) was a change of battery floating voltage of only 1 %. A change in supply frequency of only 1 %, however, produced over 2 % change in the floating voltage. Whether or not such a set will be satisfactory clearly depends upon the characteristic of the frequency error of the mains to which it is connected. The effect of the change of frequency is not so serious as it might appear, however, since the periods when the frequency is high will be balanced by the periods when it is low; and, since the change of voltage with frequency is approximately linear, the net effect on the battery will not be either to charge or to discharge it. Nevertheless, it is important to know the frequency-deviation characteristic of the supply in order to decide whether the set will be satisfactory.

The second application is in connection with the design of resonant shunts which are used in smoothing rectified supplies to electric traction systems. The usual scheme consists of a series choke followed by a number of tuned shunts, each of these circuits being tuned to one of the harmonics present in the output of the rectifier. (In the case of a 3-phase rectifier the circuits would be tuned to 300, 600 and 900 c./s. respectively.) The attenuation provided to the particular harmonic by any one of these tuned circuits will depend on its effective resistance, and the variation of the attenuation with the frequency of the supply will depend on the decrement of the shunt circuit. In the absence of any variation in the frequency of the supply, the optimum decrement will be determined by considerations of the cost of the coil and condenser, but when allowance has to be made for variation of frequency it may not be possible to use what would otherwise be the most economical design. In arriving at the most satisfactory design it will be necessary to bear in mind the frequency-deviation characteristic of the mains with which the set will be employed.

In connection with both these applications, as in the application mentioned in the paper, it is important to know not only what deviation can be expected at the moment but whether or not in the future the mains will probably improve. Consequently, if there is a number of such applications, supply authorities should endeavour to work not only to a certain total number of cycles in the day but also to some agreed standard deviation.

Mr. F. E. J. Ockenden: I should like to know the extent to which the accuracy of the teleprinters depends on the frequency. If the frequency synchronization is wrong, does it mean that the message received at one end will be incorrectly reproduced, or merely that the machine will cease to operate at all because the speed is exceeding a permissible deviation from the synchronous value?

I should also be interested to learn how the errors in timekeeping mentioned by Mr. Essen, and amounting to only a few thousandths of a second in the course of a day, are measured.

Mr. G. F. Shotter: I should like to suggest to Mr. Morrell that he develops this apparatus even further, so that the positive and negative errors could be separated. If this could be done it would prove particularly instructive in confirming the arguments as to the effect of load changes given in the paper. The conclusion reached by the authors, that the synchronous-motor drive would be quite satisfactory for teleprinters, should give a certain amount of satisfaction to the supply engineers responsible for frequency control. On the other hand, it seems to me that it might be a little dangerous to rely entirely on the frequency control always being kept within 0·045 %, although no doubt this point has been covered by "carry over" features in the teleprinter apparatus.

Mr. F. E. Nancarrow (*communicated*): It may be of interest to recall certain measurements of the variation of the frequency of power supply mains, perhaps the first to be carried out in this country to such a degree of accuracy, which were made at the Radio Laboratory, Dollis Hill, in 1932.

Fig. A shows in schematic form the arrangement used for taking the observations. The supply was caused to control a multivibrator at its fundamental frequency, and the 20th harmonic was selected and amplified to equal in magnitude an amplified output taken from a 1 000-cycle tuning fork. The latter, which was the frequency standard of the Laboratory, had a frequency which was known to within 1 part in 10^6. These two outputs were combined at the input of a rectifying valve, and the beats obtained in the output of this valve were caused to actuate a relay which in turn operated one siphon of a double siphon-recorder. The second siphon

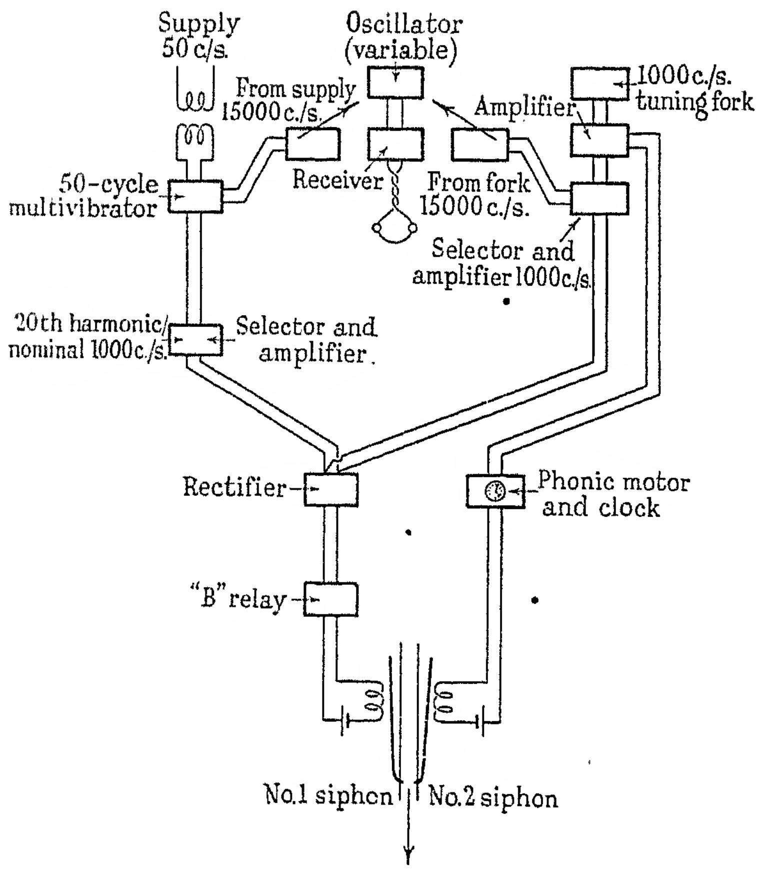


Fig. A

of the recorder was caused to record seconds, which were obtained from the contacts of a phonic motor driven from the output of the 1 000-cycle tuning fork.

The determination of the sign of the variation, i.e.

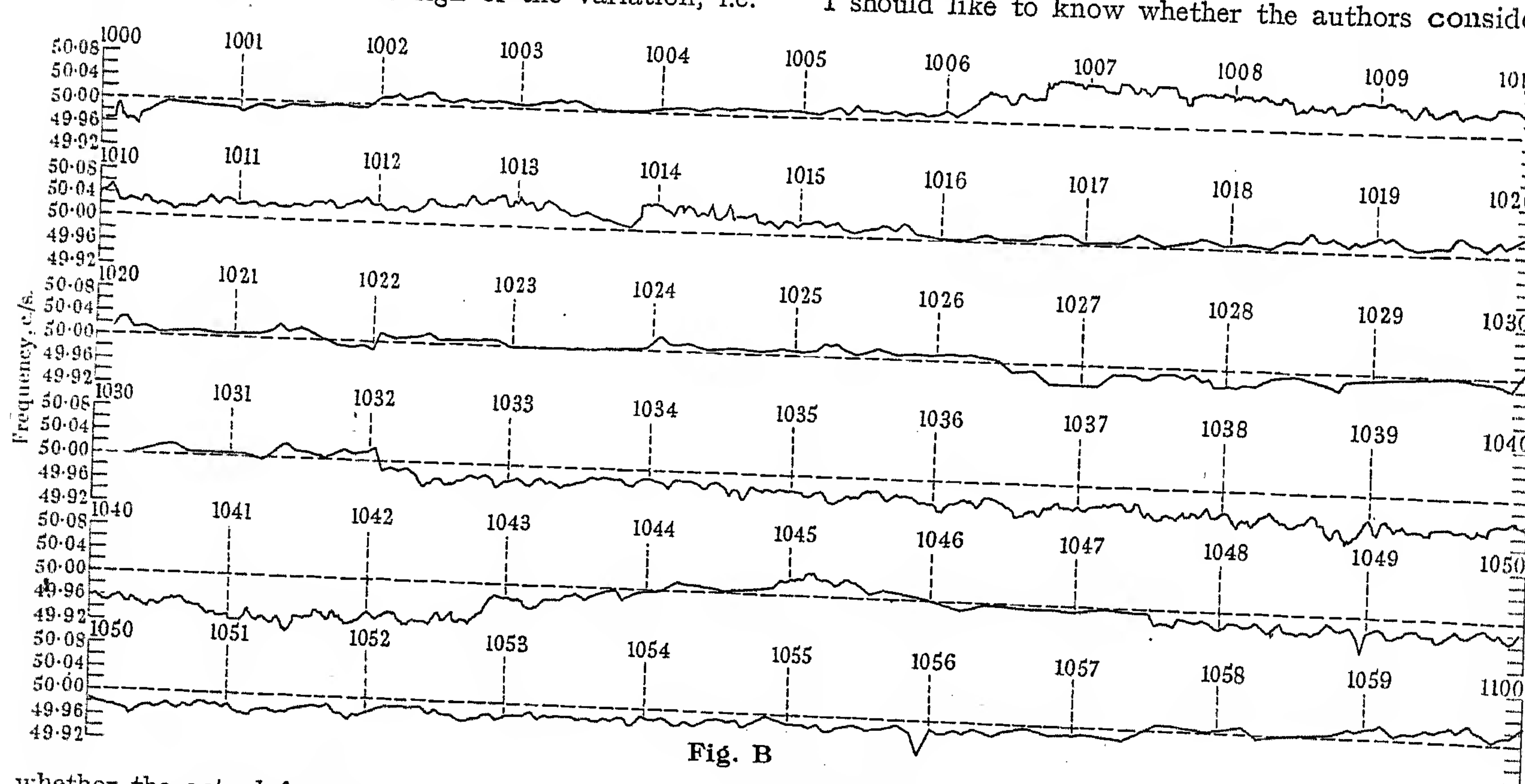


Fig. B

whether the actual frequency was above or below the nominal, was carried out by selecting the 300th harmonic of the multivibrator frequency and comparing it with the 15th harmonic of the standard tuning fork. This was done by alternately beating the output of an oscillator with one and the other and noting the tuning in each case which gave synchronism. This aural observation was carried on continuously during the recording on the tape of the siphon recorder, and the tape suitably marked.

Fig. B shows a typical result of an hour's observation taken between 10 a.m. and 11 a.m. on the 1st June, 1932. The frequency varied between 49·909 and 50·073 c./s., representing maximum variations from nominal frequency of − 0·182 % and + 0·146 % respectively. It is interesting to note that these results correspond to the results obtained by the authors in their earlier measurements, although at that time there did not appear to be the higher-value variations such as the authors indicate are possible to-day.

The labour and patience involved in analysing the tape records was, of course, great, and the recording device described by the authors avoids this altogether and enables observations to be carried out over prolonged periods without attention and with the answer always available for inspection. It would, however, perhaps make the device even more useful if some means could be incorporated whereby the sign of the variation could be given.

Mr. P. d'E. Stowell (*communicated*): The instrument described in the paper is a considerable advance on other forms of recording instrument, as it allows the record to be handled mathematically with the minimum of trouble. I am sure that there is a wide field for instruments of this type for numerous other applications than frequency recording. They are in fact ideal in all cases except those in which correlation with time is the primary concern.

I should like to know whether the authors consider that the differences between the frequency errors are really significant. The number of observations in each period seems to be such that the standard error of the standard deviations will be considerably less than the differences, but it would be interesting to know that this is really so.

Comparing the day, night and week-end periods, the authors suggest that the greatest error would be expected

during the day period, when there is a maximum change of load. Reference to system load curves will show, however, that the maximum changes of load do not occur during the period 9 a.m. to 5 p.m. In fact, if the coefficient of variation of the system load is estimated from the winter curves given in Fig. 9 of Mr. Johnstone Wright's Inaugural Address,* the following comparison is obtained with the figures given in the paper.

Period	Coefficient of variation of load	Standard deviation of frequency error
Day	11 %	0·115 %
Night	47 %	0·100 %
Week-end ..	38 %	0·107 %

This does not seem to indicate any positive correlation between frequency and load variations. If there is correlation it appears to be negative.

Again, in comparing period No. 2 with period No. 3 the authors point out that the higher frequency error in the latter is probably due to the grid operating as a larger unit at that time. I should have expected that the greater the extent of, or the greater the total load on, the system the less should be the inherent frequency-error even when the load is changing rapidly, because each of the inherent errors in load forecasting should have a smaller effect on the system as a whole.

I shall be interested to see the figures for 1940, when they are published, as I take it that Table 2 does not actually refer to period No. 4, as is stated.† The standard deviation and class intervals suggest that Table 2 refers to period No. 3.

Mr. F. O. Morrell (*in reply*): Dr. Radley is probably correct when he suggests that the readings of frequency error fall on a curve which is the sum of two normal-error curves. This has been confirmed in the case of Fig. 3, where it has been found that two curves produce an appreciably better fit. It is thought, however, that the improvement obtained does not justify a departure from the essential simplicity of the single normal-error curve.

His further suggestion that the controlling-station operator adjusts the machines to frequencies above or below 50 c./s., depending on whether the mains-driven clock is slow or fast, would seem to indicate that some improvement in the accuracy of the mains frequency could be obtained by reducing the maximum permissible time-error, and thus reducing the frequency-change required to correct the error.

I have to thank Mr. Forrest for his amplification of that part of the paper concerning the interconnection of the grid-system areas. He has also answered Dr. Radley's question regarding the trend in the accuracy of the mains frequency. It is agreed that a useful feature of the instrument lies in the ease with which it enables different systems and methods of control to be compared. This is due not only to the form in which the record is given, but also to the statistical treatment of the results.

The discrepancy between the results given by the C.E.B. recorders and the Post Office instrument has been accounted for. The error occurred mainly in the duration of the counting period, which, just previously, had been reduced from 10 to 5 sec.

The supply mains would, as Mr. Hope-Jones states, be extremely valuable in radio and television laboratories if their frequency were sufficiently accurate; it is thought, however, that the required improvement is more than can reasonably be expected. Nevertheless, at the present time use is made of the mains frequency for certain purposes. Although synchronous motors have not yet been used on teleprinters, except experimentally, the speed of governed d.c. motors is checked and adjusted by means of an instrument called a synchroscope, in which the mains frequency is the accepted standard.

Mr. Carter quotes two further instances where a knowledge of the probable accuracy of the mains frequency is of importance in the design of apparatus. Attention is drawn to his implication that supply authorities should work to an error-distribution curve having a specified standard deviation rather than a definite maximum error.

In reply to Mr. Ockenden, the effect of speed errors in teleprinters needs some amplification. Teleprinter signals transmitted over a line suffer distortion due to various causes, and the total distortion must be strictly limited if the receiving machine is to reproduce the message without error. Difference of speed between the transmitting and receiving machines is equivalent to signal distortion, and therefore the greater the difference the less will be the permissible distortion from other sources. Before a machine would fail on account of speed error alone the speed difference would have to exceed 6 %.

Regarding Mr. Shotter's reference to the danger of relying on the mains to drive synchronous teleprinter motors, it should be stated that in important offices it is always necessary to provide a reserve power supply to cover mains failures; a similar reserve for synchronous motors would cover any prolonged period when, owing to fault conditions, the frequency error was excessive. Momentary errors in excess of 0·45 % would probably not cause any noticeable failure of the telegraph system.

The earlier tests and records to which Mr. Nancarrow refers are of great interest. They were well known to me before the present instrument, which works on the same general principles, was designed. The labour and patience which, as Mr. Nancarrow states, were required in analysing the earlier records were largely responsible for the production of the automatic recorder. He and Mr. Shotter will be interested to learn that a similar instrument, but one which records also the sign of the frequency error, has been designed. It will be described by Mr. W. E. Finlason in the January, 1941, issue of the *Post Office Electrical Engineers' Journal*.

My thanks are due to Mr. Stowell for his remarks on the value of recording instruments of this type. He raises an important point on the application of statistical methods to engineering problems. It is true that the standard errors of the standard deviations are considerably less than the differences obtained, but this is not unexpected. The value of calculating standard errors lies mainly in the ease with which future samples may be checked, but it is essential that the samples be drawn from the same universe or one which is in statistical equilibrium, and this is impossible in the case under discussion. Alternatively, if subsequent measurements show variations in statistics exceeding

* *Journal I.E.E.*, 1940, **86**, p. 10.

† Corrected for the *Journal*.

the probable limits given by the standard errors, a changing universe can be suspected. Thus, comparing Figs. 4A and 5, having standard deviations of 0·106 % and 0·175 % respectively, it appears that the universe from which these samples were drawn was not in statistical equilibrium, and this was confirmed when it was found that experiments in regard to the interconnection of areas were in progress.

The inference to be drawn from this is that though at the present time frequency-errors have a certain standard deviation, one cannot assume that it will remain constant and hence predict, with a high degree of accuracy, the probable variation in the future. Nevertheless, the probability of a considerable deterioration in the future is very small, and, whilst making due allowance for the present and probable future conditions, considerable use can be made of the results which have been and are now being obtained.

As regards Mr. Stowell's remarks on the correlation of change of load and the standard deviation, it would perhaps be truer to say that the latter is roughly dependent on the rate of change of load. It is pointed out that the day figures given in the paper refer to the period between 8.0 a.m. and 5.0 p.m.

Mr. L. Essen (*in reply*): The problem of the temperature control of the quartz clock, to which reference was made by Mr. Hope-Jones, is not a difficult one. The dimensions of the quartz oscillator and the direction in which it is cut from the crystal are chosen so that the temperature coefficient of frequency changes sign at a convenient working temperature. The temperature is then controlled at this value at which the coefficient is nearly zero over a small range. The changes in the rate of the clock caused by changes of temperature of $\pm$ 0·5 deg. C. and $\pm$ 5 deg. C. from the controlled value are 0·001 sec. per day (approximately), and 0·15 sec. per day respectively. A very precise temperature control is not therefore necessary and the stability of 0·1 deg. C. obtained with a simple design of oven is more than sufficient.

The accuracy in timekeeping of a few thousandths of a second per day commented on by Mr. Ockenden can only be obtained by the continuous comparison of a group of time standards with one another and with observatory time signals. The intercomparison of the clocks can be effected by recording signals from them on a high-speed chronograph or in the case of oscillator clocks, such as the quartz clock described, by recording and measuring the beat between each pair of oscillators. By this latter method comparisons of rate accurate to 0·001 sec. per day can be made in a few minutes. One of the clocks must also be compared with time signals; but since the accuracy of these when received and recorded is of the order of 0·03 sec., it is necessary to average the results over monthly intervals to obtain an accuracy of rate of 0·001 sec. per day. The continuous comparisons between the individual clocks show how far this average rate can be used at any time during the month. The monthly stability of a good quartz clock is of the order of 0·001 sec. per day, so that the average value obtained from time signals can be taken as the rate of the clock at any time during the month.

ELECTRIC CABLES AND FIRE RISKS: RECENT DEVELOPMENTS AND INVESTIGATIONS

By S. W. MELSOM, Member.*

(*Paper first received 2nd January, and in revised form 10th February*, 1940; *read before the* TRANSMISSION SECTION *13th March*, 1940.)

SUMMARY

Section (1) sets out the means to be taken by way of external protection to ensure that mains cables entering a power or distribution station will not be destroyed by an oil fire of short duration or help the spread of an extraneous fire. The means favoured for new installations is the use of a moulded asbestos material which has in the best degree obtainable the thermal characteristics required.

To meet the case where cables are run without exterior metal protection, for positions having special fire risks and for such special uses as for switchboard connections, a new type of cable dielectric [described in Section (2)] has been developed which of itself possesses a high degree of fire resistance. The material is of a rubber-like nature, and the dimensions of the cable and the technique of installation are the same as for rubber-insulated cables.

Section (3) describes a highly important series of tests made generally under conditions as nearly as possible simulating those obtaining in coal mines—an investigation made in close collaboration with H.M. Electrical Inspector of Mines. The experiments show that, in the great majority of cases, the cables withstand any transient flames such as would arise from an explosion of fire-damp, and generally that it is very difficult to set fire to a cable under conditions held fairly to simulate working conditions in a pit. In the case of trailing cables the tests have been carried through in some cases under conditions much more severe than can occur in practice. These tests have indicated that, to secure the maximum degree of safety from fire due to internal faults, a fire-resisting type of dielectric may be desirable, and that special provision may be necessary as regards both screening of the cable and the provision of earth-leakage protection.

Section (4) is a note on the cold-pouring, cold-setting type of compound recently brought into prominence for emergency repairs which may have to be made under conditions both of urgency and of atmosphere that would preclude the use of heaters of the flame type and also would not allow of the ordinary long time for cooling and topping-up on contraction.

The main features of the compound are: (*a*) That certain ingredients mixed immediately before pouring cause the compound to set after a short period from the time of mixing; (*b*) that there is little or no contraction on setting; (*c*) that the electrical characteristics, although not so high as those of the best pitch compounds, are sufficiently good for service conditions; and (*d*) that the compound has proved to have ample stability for emergency joints under all conditions likely to be encountered.

INTRODUCTION

During the last 4 years there has been general concentration on the problem of fire risks in electrical installations and on the precautions necessary to eliminate them. These problems, which apply to ships, power stations and mines, are probably mostly due to the immense spread of the use of electrical energy and the enormously increased size of the power units and of the distribution systems.

As a result of the various inquiries that have been held the encouraging news, from a cable maker's point of view, has emerged that nowadays the fire risk due to faulty cables is exceedingly small, so small in fact that it may be almost ignored, and that, so far as cables are concerned, the real precautions to be taken are in respect of the spread of extraneous fire along the cable.

So far as ships are concerned, shipping records justly draw attention to the proud record of British shipping in this respect; regarding power stations, the report of the Electricity Commissioners does not call for any special protection from fires arising within cables; and, as for mines, all the evidence of fires in mines has exonerated cables.

An additional piece of evidence in this direction is provided by the criticisms of the introduction of a cable with fire-resisting dielectric made in some quarters, on the ground that fires with vulcanized-rubber cables are practically unknown and that therefore a better article is not required.

However satisfactory the general volume of proof may be, it will be obvious that the cable-making industry was bound to make all possible investigations and in particular to help in the solution of the problem of resisting the spread of an extraneous fire along a cable run.

It is for these reasons that the contents of this paper are sectionalized, since each section describes investigations and developments carried out largely at the request of one or other of the bodies charged with inquiries of one aspect or another of the problem. Taken as a whole, however, each of the various sections of the paper has its bearing on the general problem of fire risks.

(1) THE FIREPROOFING OF MAINS CABLES IN POWER STATIONS

Although a great deal of work on this subject had been done in America, mainly with a view to protecting cables from fire due to breakdown of adjacent cables, more particularly in the manholes which are part of the large duct systems prevalent in the United States, it was not until 1937 that the subject was given serious consideration in this country. The Committee set up by the Electricity Commissioners as a result of painful experience worked energetically at the problem and we owe much to this Committee for the excellent way in which the whole

* Cable Makers' Association.

problem was clarified, and for the resultant proper provision for protection against fire.

It may be assumed from the published recommendations of the Commission that the main problems to be faced so far as cables are concerned arise from extraneous fires mainly due to flowing burning oil in a station or substation.

As a result of the measures taken for protection against oil fires it is expected that, if and when such fires do occur, they will be of comparatively short duration so that the protection necessary for the cable is something which will withstand a fire for a short time without damage to the cable, or, at the very worst, ensure that any danger is kept within bounds so that the dielectric of the cable does not contribute to the general conflagration.

The recommendations of the Commissioners were made after full consultation with the industry, and with them the cable makers are in full agreement. It may, however, be of interest to discuss the manner of giving effect to these recommendations and the effect that the protection may have on the performance of the cables under normal operating conditions.

The essential requirement for the fireproofing of lead-sheathed paper-impregnated cables is that the fireproofing should be sufficiently heat-resisting fully to protect the cable, of sufficiently low thermal resistivity so as not to decrease unduly the current rating of the cable, and either be of such composition as not to set up corrosion of the lead sheath or, alternatively, be provided with protection against such corrosion.

A combination of all these properties was not very easy to find, and a good deal of investigation was required before the best materials were found. Also in some cases the use of the best method was not possible on systems already installed, and alternative methods had to be sought.

Dealing with the question of cables emerging from the floor and going upwards to connect to switchgear, etc., or to other cables run in the vicinity of such gear, the method selected for new installations and for existing installations where space was available was to use moulded asbestos supplied by the makers in the form of split tubes which could be clamped around the exposed length of the cable. Apart from ease of fitting and the comparatively pleasing finish of the job, this material represents the nearest approach to the ideal characteristics mentioned above. Magnesia has probably a higher degree of resistance to fire than the asbestos mouldings, but the thermal resistivity of the material is so high that the current rating of the cable would be greatly reduced.

The thermal resistivity of moulded asbestos is of the order of 700 thermal ohms, a value which, with the thickness of material used, would normally decrease the current rating of the cables by about 20%. Against this, however, may be offset the normal increase of rating due to the fact that the cables in the ground are probably grouped, whereas when they are taken to switchgear they are separated by a distance sufficient to free them from "proximity heating." This generalization, however, must not be carried too far, since if the cables in the run were separated throughout and operated at or near their maximum current the asbestos-covered section would reduce the permissible current to an extent which would require serious consideration.

The fire-resisting properties of the moulded asbestos material appear to be extremely good. From figures quoted by the makers the white asbestos material only begins to suffer damage when subjected to a temperature of 2 500° F., and the asbestos compound can withstand much higher temperatures for short periods.

Tests carried out by the E.R.A. on cables protected by moulded asbestos exposed to a serious oil fire showed that, while parts of the burning enclosure reached a temperature of about 1 100° F., the highest recorded temperature on the protected cable sheath was 176° F. More severe tests of the same material used as a protective covering for steel girders showed that after a period of more than 4 hours' exposure, during which the ambient temperature rose to 2 100° F., the temperature of the protected ironwork was only 850° F.

It should, however, be noted that the material is somewhat alkaline and that, to ensure protection against corrosion, the lead sheath of the cable should first be protected with a layer of bitumen paint and wrapped with one layer of bituminized tape.

An alternative method for new installations is to apply to the lead sheath of any portion of an underground cable which may be exposed to fire risk inside a station, the following finish in place of the normal waterproof coverings:—

> The lead sheath shall be coated with the normal waterproof compound over which shall be applied two layers of hessian tape thoroughly compounded with a suitable fire-resisting compound which shall have no deleterious effect on the sheathing. A complete layer of uncompounded armouring wires shall be applied over this bedding. Such armouring wires shall consist of galvanized steel in the case of twin and multi-core cables, and also for single-core cables used on d.c. circuits. For single-core cables used on a.c. circuits the armouring wires must generally be of non-magnetic material.
>
> All the cables on which this class of finish is desired should preferably be wire-armoured throughout their whole length.
>
> Where armouring is not employed the above bedding should be used, modified to permit the use of a fire-resisting cotton tape overall, the cotton tape being employed to improve the appearance of the finish.

In another Section of the paper the protective effect of armour wire is clearly shown and, although a plain lead-sheathed cable is generally used near switchgear, this method of protection is worthy of serious consideration.

For existing installations in which the conditions of erection are such as not to allow the use of moulded asbestos a very good degree of fire resistance can be ensured by stripping off all the existing protective wrappings to the armour (or lead as the case may be), painting the cable with bitumen paint and wrapping with a layer of bituminized tape, and then applying two layers of asbestos tape with a sensible overlap. The asbestos should be freely painted with silica paint.

The remainder of the instructions issued by the Electricity Commissioners do not require any comment from a cable-laying point of view, and it need only be pointed out that enclosure in such materials as weak cement which have a quite low thermal resistivity will not adversely affect the current rating of the cable so enclosed; in fact it might, under some conditions, slightly improve it. Just a word, too, on the warning regarding sand as a drainage for oil: some authorities insist that the pebbles used for this purpose should be at least ½ in. diameter and claim that sand or granite chippings impede the drainage of oil to a dangerous degree.

(2) FIRE-RESISTING CABLES

In recent years increased attention has been given to the question of the extent to which electrical installations in buildings, ships, mines, etc., may be responsible for fires, and all cable makers are naturally desirous that the cables used shall have the minimum tendency either to initiate a fire as the result of an electrical failure in the circuit or to spread a fire which may have arisen from some extraneous source.

Rubber-insulated cables have proved deservedly popular on account of their satisfactory electrical properties, ease of installation, and long life in service. While there has been a gratifying freedom from serious troubles it has been recognized that it is a somewhat difficult matter to impart to rubber-insulated cables a high degree of fire resistance while at the same time retaining their other desirable properties. Although a standard vulcanized-rubber dielectric is not inflammable in the sense in which certain materials are recognized as being inflammable, it does not possess any specific fire-resisting or self-extinguishing properties. Consequently the fire-resisting or flame-retarding properties of cables with standard vulcanized-rubber dielectric depend upon the outer protection which, for wiring sizes of cable, usually takes the form of a single or double braiding of cotton, wool or asbestos, treated with some form of fire-resisting compound. While such cables have obtained a wide use and represent the best that can be done with standard rubber dielectric, it has been felt by cable makers that they do not represent the best technical solution of the problem of fire-resisting cables, since they are not fire-resisting at exposed ends. Moreover, to obtain the best results it is necessary to have a relatively thick outer protection, which naturally increases the overall diameter, and this, in turn, may introduce installation difficulties, to say nothing of the fact that the double braiding operation, which is necessary to obtain the best results, naturally retards production. It seemed clear, therefore, that if it were possible to develop a cable using a dielectric having the properties associated with rubber, with the additional property of inherent fire-resistance, it would represent a definite step forward.

Cables having mineral dielectrics, e.g. asbestos or magnesia, have been commercially available for some time, but although such cables have obviously very satisfactory properties so far as fire-resistance is concerned they require special end-sealing to give protection from moisture and, in addition, tend to be rigid, which renders installation more difficult. For these reasons such cables have a restricted use, and the standard types of rubber-insulated cables retain their popularity for general purposes.

For a number of years the research staffs of the associated firms of cable makers have been attempting to produce fire-resisting or self-extinguishing rubber compounds, and quite a fair degree of success has been obtained in imparting these properties to rubber. The fundamental difficulty, however, has been that raw rubber is not self-extinguishing when once ignited, and the other materials which it is necessary to incorporate in the mix to overcome the lack of self-extinguishing properties greatly modify its other desirable properties. What is required for the basis of a successful self-extinguishing dielectric is a material which, in the raw state, has rubber-like properties with the addition of fire-resisting properties, since it is clear that, although it might prove necessary to incorporate other materials in much the same way as is done with rubber, it would not be necessary to sacrifice the rubber-like properties in order to obtain the fire-resistance.

Several synthetic materials having generally the properties outlined above have been produced over the past 5–10 years and have naturally received very close investigation in order to assess their suitability for application to cables. Not all proved so useful as their initial examination suggested, but one of them proved extremely promising. Without entering into any very involved chemistry, it may be said that this material is obtained by the polymerization of 2-chlorobutadiene, which is represented by the formula $CH_2 = C\,Cl - CH = CH_2$. It thus belongs to the same general chemical group as "rubber," which is 2-methylbutadiene $CH_2 = C\,CH_3 - CH = CH_2$. This similarity in molecular constitution between the synthetic material and natural rubber is reflected in the fact that in the raw state the material is very similar in its physical properties to raw rubber. The raw material is unsuited to the manufacture of cables and has to be converted into a suitable "mix." However, as pointed out earlier, since the material is already fire-resisting it is not necessary to obtain the fire-resistance at the expense of other properties. Extensive tests have shown that this synthetic material is more resistant than rubber to deleterious influences such as heat, oxygen, light, oil, etc., and although observations regarding its life under natural conditions are necessarily restricted to some 5 to 6 years, these observations have fully confirmed the conclusions, drawn from laboratory tests, that a satisfactory life may be anticipated from cable in which the synthetic material is used. Its electrical properties are interesting, but in one respect unfortunate, for while the breakdown value is comparable with that of rubber the insulation resistance is so low that the material would be unacceptable if used alone as a dielectric for general wiring work.

A large number of experiments were carried out in which cables were made with dielectrics using different "mixes" derived from the basic material, and also in which different types of mix were combined with natural rubber with the object of maintaining a high degree of self-extinguishing properties and combining these with satisfactory electrical properties. As a result it has been possible to arrive at a construction of dielectric which,

while self-extinguishing to a very high degree, also complies with all recognized electrical pressure tests for rubber cables and has an insulation resistance which, although somewhat lower than that normally associated with vulcanized rubber, is ample for all wiring purposes. It was further found possible to obtain these properties with the new dielectric applied to the same radial thicknesses as the standard vulcanized rubber.

As mentioned earlier, the way in which a cable might influence a fire is either by spreading a fire which has already started from an extraneous source, or by initiating the fire through some electrical failure. The outstanding properties of the new fire-resisting dielectric in neither spreading an existing fire nor initiating one can be demonstrated by means of laboratory tests.

An example of a test is shown in Fig. 1 (see Plate 1, facing page 524) in which a sample of the new fire-resisting dielectric without any external coverings (left-hand sample) was subjected to an external flame. Not only was the fire-resisting dielectric difficult to ignite, but all action ceased in about 30 seconds and the dielectric was impervious to continued application of the burner, only that part in the immediate vicinity of the flame being affected. Under the same conditions the standard vulcanized-rubber dielectric (right-hand sample in Fig. 1) continued to burn. Similar results are obtained if an internal arc is caused to occur, e.g. from the breaking of the conductor. As the dielectric is an organic material the portion in the immediate vicinity of the arc is, of course, destroyed by the intense heat of the arc, but when the latter ceases the dielectric is also self-extinguished and the cable will not convey flame to another part of the installation.

Having developed a satisfactory fire-resisting dielectric, the next step in the development of the cable was to investigate the outer coverings. It was clear that the same outer coverings could be applied as are normally applied to standard vulcanized-rubber cables, although obviously the coverings would be restricted to those of a fire-resisting nature. Theoretical considerations suggested that as the dielectric possessed such good fire-resisting properties it would not be necessary to rely on the outer coverings as is the case with standard rubber dielectric. It was found that an outer covering of braid and fire-resisting compound is not really necessary from the fire-resisting standpoint, but such a covering is nevertheless applied in order to afford some mechanical protection to the dielectric during installation or to act as a "key" for further paint which may be applied after installation. The fact that "fire-resisting insulated" cables can be manufactured to the same overall dimensions as those of standard vulcanized-rubber cables, represents a definite step forward. To quote a typical example, it has been found that a cable made with fire-resisting dielectric and a single cotton braid treated with fire-resisting compound has better fire-resisting properties than a cable made with standard rubber dielectric and two braids each treated with fire-resisting compound, and it is to be further noted that, in addition to better fire-resistance, the fire-resisting insulated cable has the advantage of being smaller in diameter and of being manufactured at a higher rate of production.

A further point of superiority over cables made with mineral dielectrics is that so far as installation is concerned the new fire-resisting insulated cable can be regarded as identical with the standard rubber-insulated type, since the cable is just as flexible and requires no more protection at ends than is normally given to rubber-insulated cables.

So far development has been restricted to the sizes and types of cable normally used in ordinary wiring work, i.e. braided and compounded or metal-sheathed, but development is proceeding on other types.

(3) THE FIRE-RESISTING PROPERTIES OF CABLES USED IN COAL MINES

Fires which have occurred in coal mines during recent years with deplorable loss of life have raised in some minds the question as to how far the electrical cables have been responsible either for initiating a fire or for conveying an existing fire from one part of the mine to another. Some time ago H.M. Electrical Inspector of Mines (Mr. Horsley) inquired whether the cable makers would be willing to carry out experiments with a view to obtaining data which would answer certain specific questions. This co-operation was willingly afforded, and this Section of the paper deals with the work which was carried out as the result of a research programme drawn up after discussion between a suitable Research Committee and Mr. Horsley, whose close co-operation and keen interest has been most highly appreciated.

It will of course be clear that the most important feature of the co-operation has been the correlation of the methods of test with the conditions in a coal mine, the type of fire which occurs there, and the mechanical usage to which cables are subjected as part of the normal working of a coal mine.

Cables used for permanent installation in shafts and "in-bye" normally have a single wire armouring for external mechanical protection. The armouring generally has a further textile covering thoroughly impregnated with a pitch type of compound to give the maximum protection against corrosion. It was natural, therefore, that the first question that arose was whether the external wrappings would be capable of being set on fire, and, if so, under what conditions; and further, assuming they could be set on fire, to what extent were they likely to convey flame.

The cables used for this section of the work consisted of 0·06-sq. in. standard rubber-insulated, single-wire-armoured cable, and paper-insulated lead-covered cable of the same conductor size but lead-sheathed and single-wire armoured. The testing procedure consisted in laying 1-yard lengths of the cable horizontally about 1 ft. above a laboratory bench and subjecting them to the action of three bunsen burners (adjusted so as to melt a piece of 0·028 in. copper wire in 5 seconds) spaced equally round the cable at one place. There was no sign of ignition for about 15 seconds, after which the cable began to drop burning compound, which was self-extinguished almost immediately on reaching the bench. Fig. 2 (Plate 1) shows a typical test about 30 seconds after commencement. The compound is reasonably well alight. In several instances the cable was removed from the burners when in this condition in order to ascertain whether the wrappings would continue to burn, but in

Plate 1

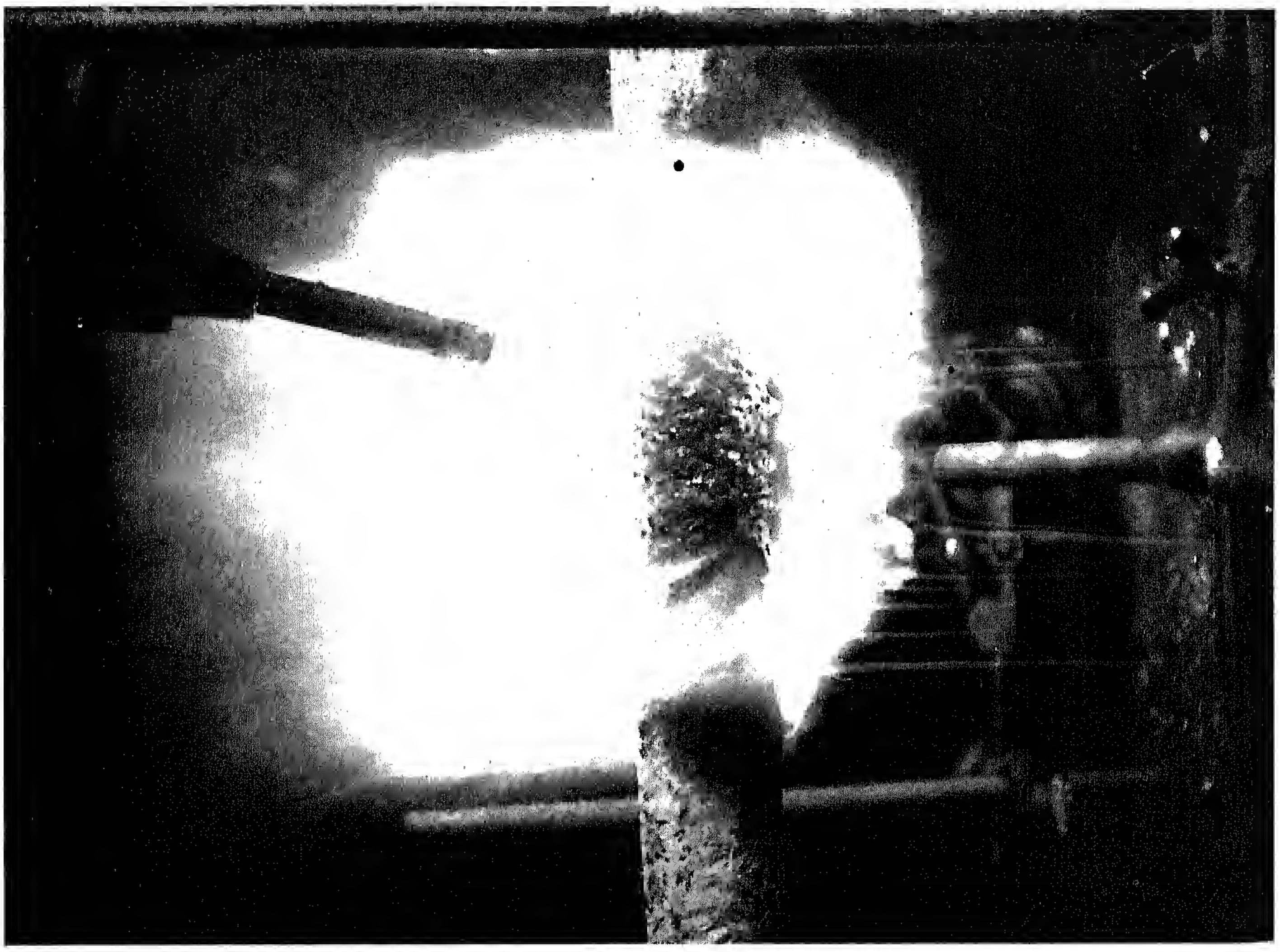


Fig. 2.—Standard vulcanized-rubber, steel-wire-armoured cable 30 sec after start of flame-resisting test.

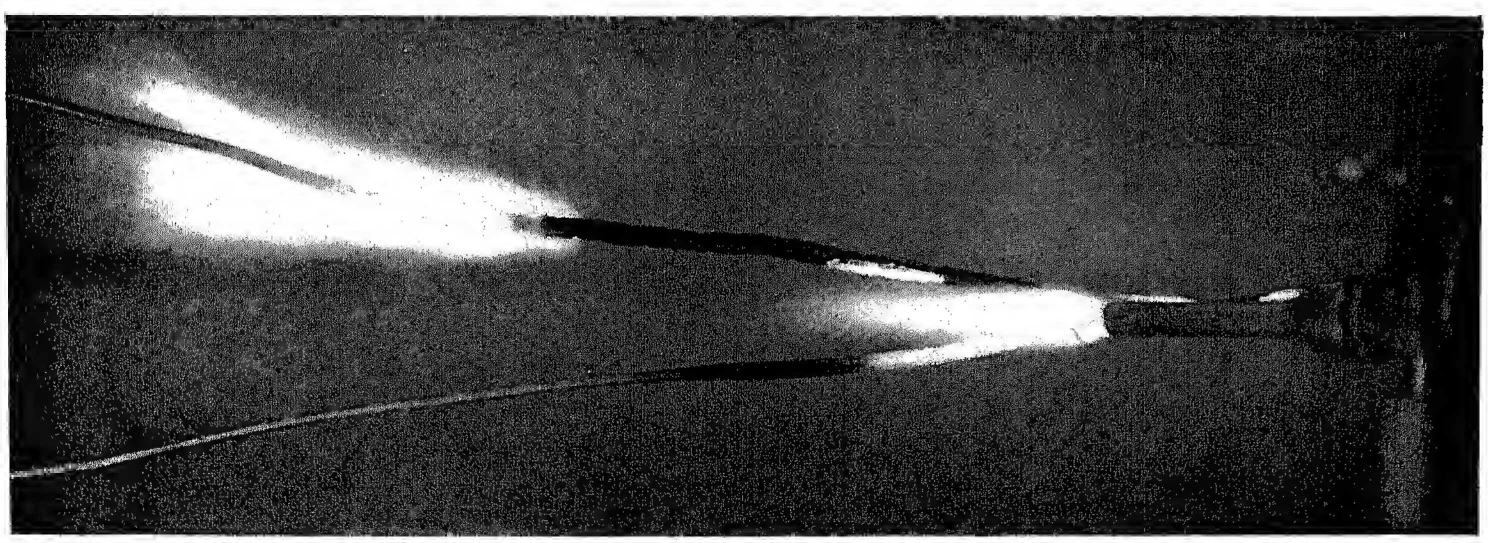


Fig. 1.—Flame tests on vulcanized-rubber cable.

Left-hand core, fire-resisting dielectric.
Right-hand core, standardized rubber dielectric.

Plate 2

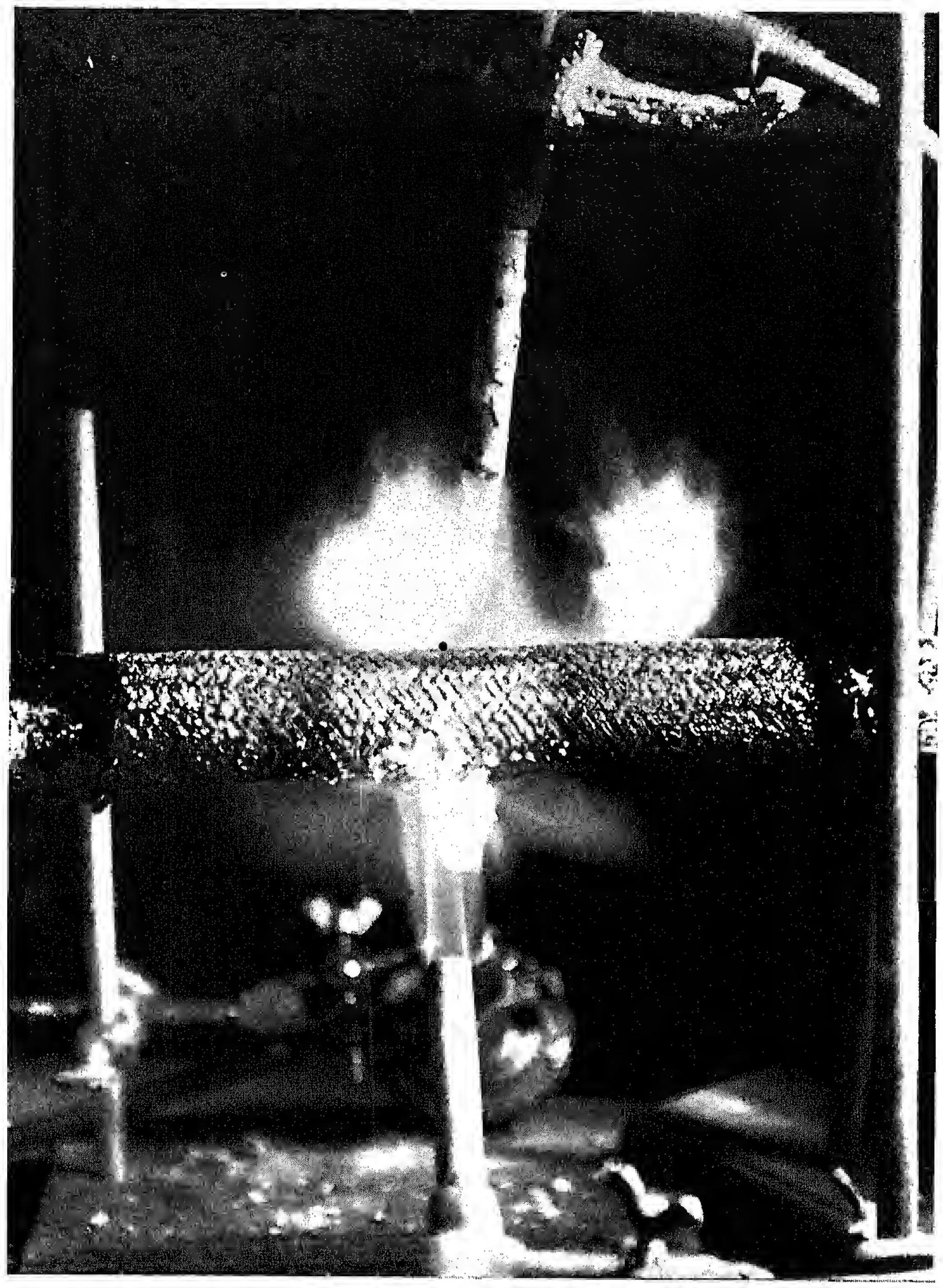


Fig. 3.—Standard vulcanized-rubber, steel-wire-armoured cable as Fig. 2, but 10 min. after start.

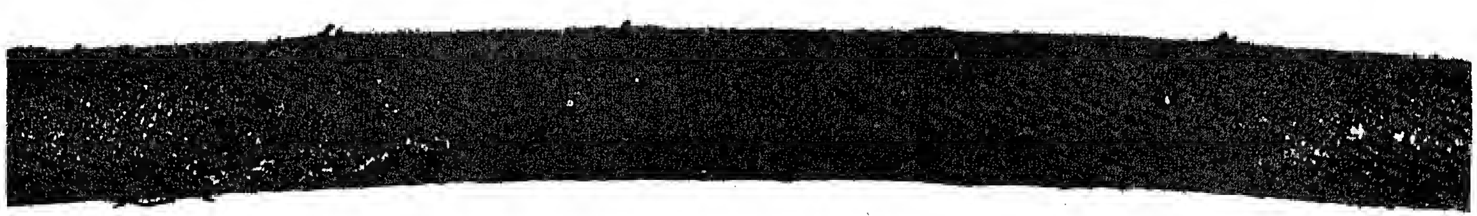


Fig. 4.—Standard vulcanized-rubber mining cable after 10-min. flame test. Three burners, armouring removed.

Fig. 5.—Standard vulcanized-rubber mining cable after 10-min. flame test. Three burners, bedding removed.

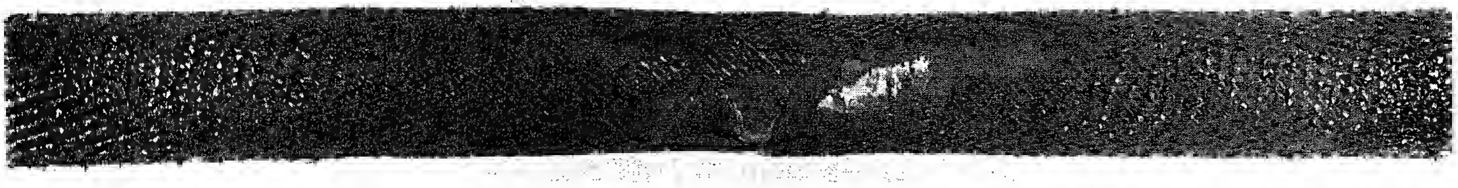


Fig. 6.—Standard paper-insulated, lead-sheathed cable after flame test. Three burners, armouring removed.

Fig. 7.—Standard paper-insulated, lead-sheathed cable after flame test. Three burners, hessian removed.

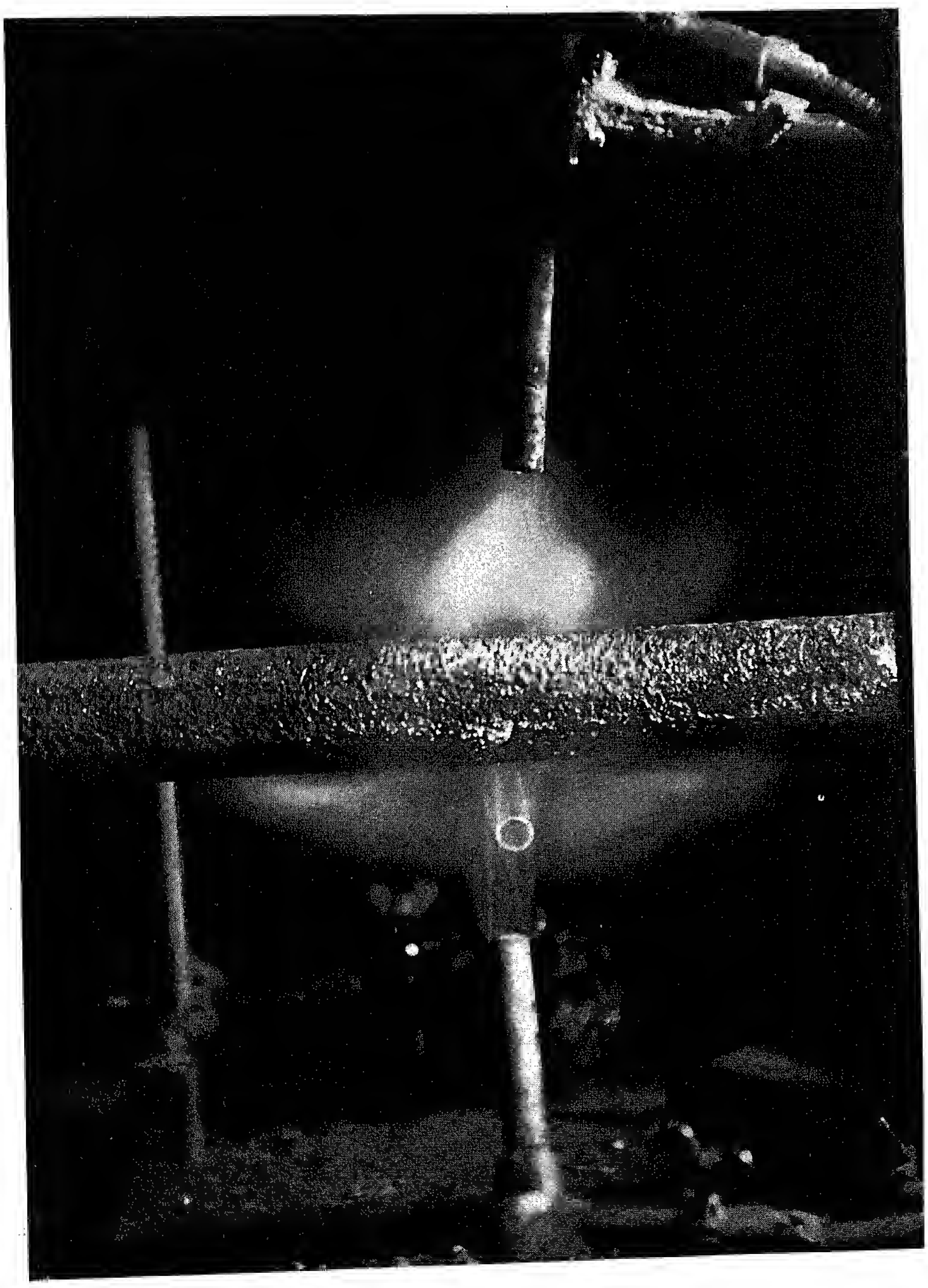
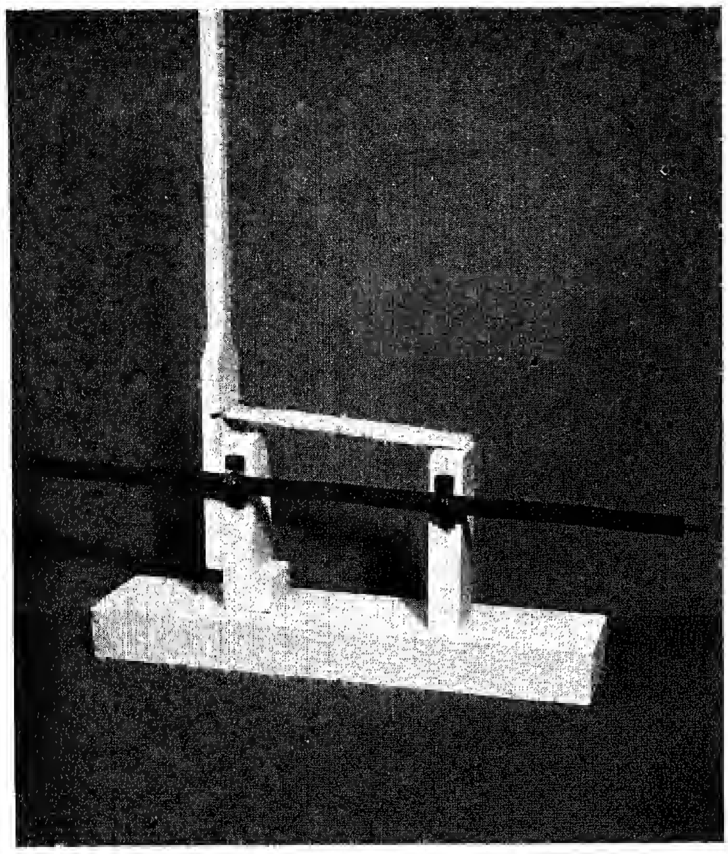
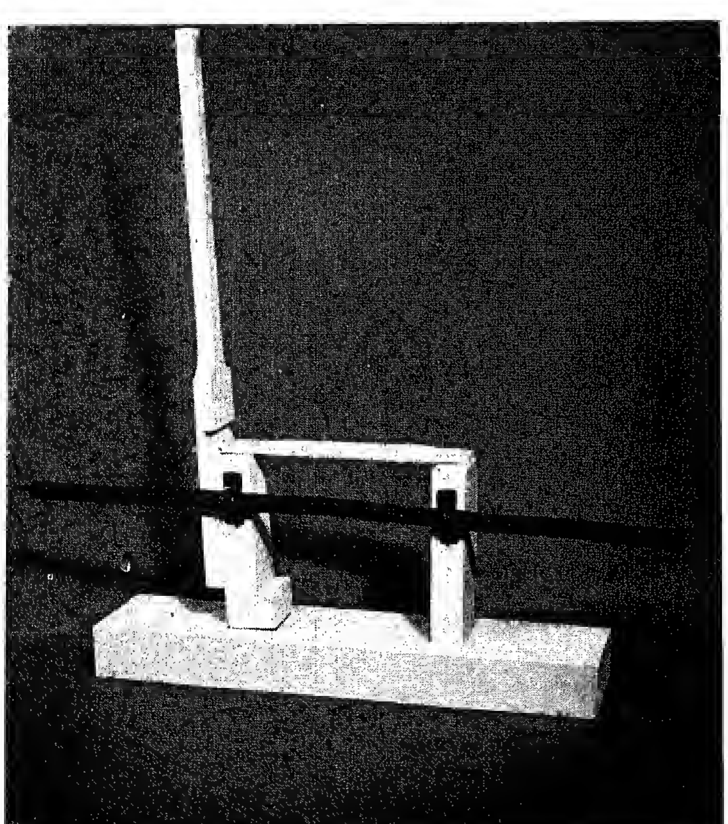


Fig. 8.—Standard vulcanized-rubber, steel-wire-armoured mining cable treated with fire-resisting paint, 30 sec. after start of test.

Plate 4





Figs. 9 and **10**.—Apparatus for arcing tests on imitation trailing cable.

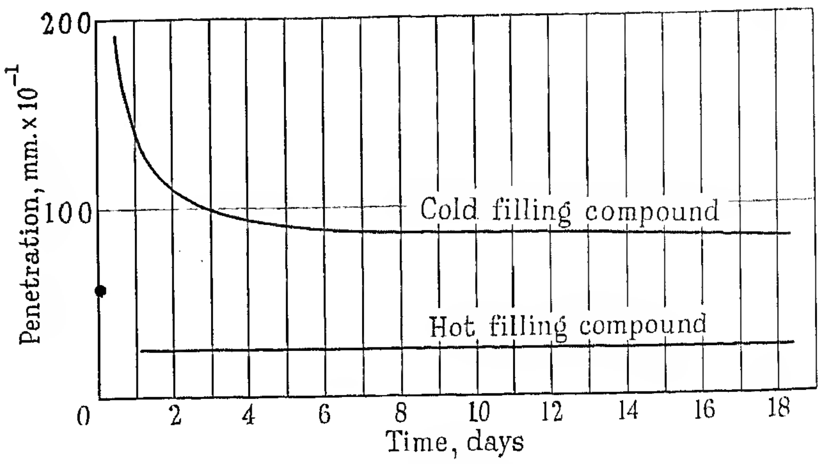


Fig. 11.—Curve showing the penetration of hot and cold filling compounds.

Fig. 12.—66-kV single-core emergency joint.

every case they were self-extinguished in about 1 minute and there was no tendency for the flame to travel along the cable. In other tests the burners were left in position around the cable, and under these conditions the flame spread for a short distance on each side of the burners. All samples were, however, self-extinguished in about 6 to 8 minutes, and a total length of only some 7 to 8 inches was affected. Fig. 3 (Plate 2) shows a typical test 10 minutes after commencement. It will be seen that ignition is completed and the cable has been affected for only some 3 to 4 in. on each side of the burners. In other experiments similar tests were applied to cable in which the wrappings were previously cut about with a knife so as to expose free ends, with the object of simulating the wrappings when in a frayed condition. With a reasonable degree of fraying the behaviour of the cable was the same as that of an unfrayed sample, and it was not until the wrappings had been badly mutilated that they could be made to spread flame. Even under these conditions the rate of spread was relatively slow, being of the order of 1 ft. in 3 minutes, and burning was restricted to the cut edges of the wrappings.

In another series of tests the cable was tested in a vertical position. Two burners were applied to the cable for 30-second periods, together with a longer period, bringing the total time of application up to 5 minutes. Under these conditions the wrappings treated with standard petroleum pitch compounds were self-extinguished without appreciable spread of flame.

It will have been noted that the application of a hot external flame for about 15 seconds was necessary to ignite the compound on the wrappings of a standard C.M.A. cable, so that it seems reasonable to conclude that such wrappings would not become ignited as a result of a transient flame such as would arise, for example, from an explosion of fire-damp. The behaviour of the cables under the various tests applied indicates that relatively prolonged application of external flame, which implies an already existing severe fire, is necessary to ignite the wrappings, and it seems that if the source of flame is local the cable will not, in general, convey flame away from this spot. With more severe and general conflagration the cable might well become ignited and convey flame, but the conditions envisaged would be such that any effect resulting from the cable would probably be relatively unimportant.

In addition to observing the extent to which the cables would convey flame, it was thought of interest to ascertain to what extent they were themselves damaged. Fig. 4 (Plate 2) shows a typical rubber cable which has been subjected to 3 burners for 10 minutes, followed by removal of the outer wrappings and armouring wires. It will be noted that the compound on the hessian bedding has been melted away for some 3 to 4 in. on each side of the point of application of the flame, but beyond this nothing has happened. Fig. 5 (Plate 2) shows the same cable after removal of the textile wrappings over the tough-rubber sheath. The latter shows surface charring just at the point of application of the burners, but the cable is otherwise unaffected. Fig. 6 and Fig. 7 (Plate 3) show corresponding photographs of a lead-sheathed, paper-insulated cable. After removal of the armouring, the hessian bedding over the lead was burnt away in the vicinity of the applied flame and it appeared that the lead had also been melted. Fig. 7, showing the cable after removal of the bedding, confirms this, showing the lead melted away locally. Further examination showed that the belt papers were charred, but the actual core insulating papers were unaffected.

While the tests indicated that the wrappings treated with petroleum pitch compound were appreciably more fire-resisting than might have been expected, the next logical step was to investigate the use of compounds having greater fire resistance on the wrappings. Such compounds are already used on certain types of cable. Tests similar to those already described were applied to rubber cables which were of standard construction apart from the replacement of the pitch type of compound by the fire-resisting compound. Fig. 8 (Plate 3) shows a sample of cable 30 seconds after application of the burners, and it will be seen that there is complete absence of burning compound; even continued application failed to ignite the wrappings. It would seem that the wrappings can for practical purposes be rendered non-ignitable by the use of fire-resisting paint compounds. These are not so resistant to the passage of water as are the standard petroleum pitch type which, as mentioned earlier, are used specifically to give protection against corrosion. Consequently the use of these fire-resisting compounds in place of the present standard types would render the armouring wires more liable to corrosion from acid waters, etc. The author is not in a position to say whether the trouble which may arise from this source would more than offset any advantage which might be gained from increased fire resistance.

Generally the results draw attention to the extraordinary fire-protective qualities of the armour wires. Not only are the exterior wrappings and their impregnating compound rendered fire-resisting to a high degree, but the inside of the cable is almost completely protected.

The work so far described concerns the possible tendency of the armoured cable to spread an already existing fire. The next question which arises is whether a core-to-core arc, which might arise, for instance, as a result of mechanical damage to the cable, would set the latter on fire, this in its turn initiating a larger fire. The cables for this part of the investigation consisted of 0·1-sq. in. 3-core, single-wire-armoured, rubber-insulated, impregnated paper-insulated, and vulcanized-bitumen-insulated cables with standard petroleum pitch finish. As a result of a number of preliminary tests made to obtain a rough idea of the magnitude of the possible effects, artificial short-circuits were made by driving 0·064-in. copper wire through two of the three cores prior to completion of the cable. To prevent vapour, etc., being forced out at the end of the cable as the result of the arc, the test pieces were made 10 to 12 ft. long, the artificial short-circuit being in the middle of the length. For the actual test the pieces of cable were laid on a concrete floor and the two short-circuited conductors connected to a 600-volt supply obtained from a 250-kVA, single-phase, 50-cycle alternator, giving a short-circuit current of between 1 200 and 2 000 amperes. Under the worst conditions the short-circuit caused a relatively violent explosion, burst the cable, burnt away

the conductor for 2 to 3 in., and ignited the outer wrappings. These were self-extinguished, however, in periods varying from 2 to 15 minutes, and the burning did not spread away from the immediate neighbourhood of the fault. All three types of cable behaved in substantially the same way, and although the short-circuit naturally caused severe local burning of the dielectric this was not further ignited by the burning of the wrappings. It would therefore seem that, although a severe internal arc due to a short-circuit can ignite external wrappings which have been treated with petroleum pitch compounds, the wrappings will be self-extinguished and will not convey flame along the cable. The use of fire-resisting compound on the wrappings would obviously be a further safeguard against spread of fire but would not prevent local burning of the dielectric if the short-circuit were sufficiently severe to burst the outer coverings and admit air to the interior of the cable.

Flexible Cables

The matters so far described refer to fixed cables; similar questions naturally arise in connection with flexible trailing and drill cables which have an unprotected rubber sheath and are more liable to mechanical damage which might give rise to internal arcing. In the first place it was desired to obtain an idea as to the ease or otherwise with which a standard rubber sheathing would become ignited from an external source of flame of the type likely to occur in a mine. Various types of cable were tested, both armoured and unarmoured. In the first type of test 1-yard lengths were laid flat on a concrete bench and the flame of a bunsen burner, adjusted as already described, was passed continuously backwards and forwards along the surface of the cable at a rate of 1 yard in 10 to 12 seconds. All cables withstood 50 such passages without any ignition occurring. In another type of test the burner was applied for varying periods to one spot on the cable, and the behaviour of the latter noted. A large number of such tests were carried out, and the following general conclusions were arrived at:—

(1) To ignite the sheathing of a standard trailing cable even reasonably well, it is necessary to subject it to the action of a hot external flame locally for about 1 minute.

(2) The rate of spread of the flame, after removal of the external source, is relatively slow—about 1 inch in 4 to 7 minutes—and this rate appears to be subsequently unaffected by variations in time of application of the external flame.

(3) Armouring under the sheathing definitely increases the difficulty of burning, and in some cases renders the sheathing self-extinguishing even after 5 minutes' application of a hot flame locally.

(4) Even after 5 minutes' application of a hot flame locally to an unarmoured trailing cable the sheathing was not sufficiently well alight to prevent it from being blown out by the breath without undue exertion.

(5) The results suggest that the likelihood of a standard trailing cable becoming ignited as the result of a transient flame is very remote, and that even if the sheathing did become ignited the flame could be extinguished quite easily without having spread. The results further suggest that the external flame conditions necessary to get the cable really well alight are such as would arise only if there was already severe conflagration going on in the mine, in which case any secondary effect, resulting from the cable, would be relatively unimportant.

Generally the results indicated that standard rubber trailing cables have a greater degree of fire resistance than might have been expected, and it is evident that, from the standpoint of resisting an external source of ignition, the present type of cable is satisfactory. Naturally, however, the risk of a cable conveying an already existent fire would be reduced by the use of a fire-resisting sheathing, and further reference to this will be made later.

In addition to the effect of external flame, tests have also been made to determine the effect of a core-to-core arc. Samples of 0·0225-sq. in. 4-core unscreened trailing cable were used in these experiments. For the first test a sample about 5 ft. long was crushed between steel plates about 6 in. square, until core-to-core failure was known to have occurred. In passing it may be mentioned that a load of some 10 tons was necessary to do this and the cable was crushed almost flat. The cable was then connected to a 600-volt a.c. supply as described earlier in this paper, and a load of 1 cwt. dropped on to the damaged portion so as to produce a short-circuit. Under these conditions the arc burnt away the conductor for 2 to 3 in. and burst the sheathing. The cable caught alight very feebly but was self-extinguished in less than 30 seconds. In another experiment a sample which had been previously damaged by being crushed was connected to a 50-volt d.c. generator and hit violently with a sledge hammer, the cable itself lying on a steel plate. After considerable mechanical maltreatment, resulting in complete bursting of the sheath and severe damage to the conductor, it was possible by agitating the cable to produce core-to-core arcing, and by maintaining this for about 30 seconds to get the cable alight to such a degree that it would continue to burn. The main point which seemed to emerge from these experiments was the extraordinary severity of the mechanical damage necessary to cause the arc to be started.

The investigation was taken a step further by carrying out similar tests on lengths of cable made with standard rubber cores and a fire-resisting sheathing. In this case the cable burnt while the arc was maintained, but unlike the standard type was self-extinguished when the arc was broken, without the fire spreading away from the immediate vicinity, although the cable had been so badly damaged as to give free access of air to the cores. It would seem, therefore, that the use of a fire-resisting sheathing would be one way of localizing a fire which might be initiated as the result of an internal arc. In this connection it may be noted that considerable attention has been given to the production of cables having the properties associated with rubber but with improved fire resistance, and many types of rubber and rubber-like compounds have been produced experimentally both

for use as dielectrics and for sheathing. Work on dielectrics has resulted in the development of a special type of dielectric already in use for certain types of cables [see Section (2)].

One point, however, of especial interest to mining works may be mentioned here. The major difficulty so far as sheathings are concerned is the fact that hitherto fire-resisting properties have been obtained at the expense of desirable physical properties, such as tensile strength and resistance to tear. As the result of later developments, it is now possible to produce fire-resisting sheathings which, while not possessing such high tensile strength or tear resistance as the standard resilient tough-rubber sheathing, may have sufficiently good mechanical properties to allow of their use for trailing cables used in mines.

It will perhaps be admitted that the results with trailing cables, showing as they do the great difficulty in maltreating a cable so badly as to produce an internal arc, and the comparative ease with which the flame resulting from such an arc is extinguished, indicate clearly that the existing standard cables are adequate for their service. Consideration, however, of the extent to which the normal overload protection used in mines installations was suitable to clear faults of this kind led to a further series of interesting experiments, but under conditions which can hardly occur in practice. Most certainly there is no record of any such.

Four sets of samples were made up, as follows:—

(1) Standard vulcanized-rubber dielectric with standard sheath.
(2) Standard vulcanized-rubber dielectric with fire-resisting sheath.
(3) Fire-resisting dielectric with standard sheath.
(4) Fire-resisting dielectric with fire-resisting sheath.

The conductor was 0·0225 sq. in., insulated with dielectric 0·062 in. thick and having a sheath 0·15 in. thick.

The weak places were spaced every 2 ft. and, as the conductor was semi-broken before the dielectric was applied, the complete breaks could be made by moving the cable and without in any way affecting the dielectric or sheathing. This arrangement also allowed the broken ends of the conductor to be pressed together and withdrawn to start and continue the arc. In fact, by the use of the comparatively simple apparatus shown in Figs. 9 and 10 (Plate 4) the exact position of the cores could be varied at will.

In order to obtain the most severe result, the current supply was from a large 500-volt d.c. generator, and the current was intentionally maintained at low values, so that disruption, if any, should be due to a continual arc, rather than a short-duration arc of high current. The actual currents applied to the cable were therefore 4, 10·5 and 20 amp. respectively.

Three tests were carried out on each type of cable under each condition, and the results obtained are summarized below.

(1) In every test at 10·5 amp. and above, and in half of the tests at 4 amp., the sheathing was burst by the internal pressure developed from the thermal decomposition of the dielectric. This became increasingly severe with the higher currents, and at 20 amp. the bursting was relatively violent. In a few cases the violence of the explosion was sufficient to quench the arc, and after the sheath had burst no further action took place unless the arc was restarted. This effect seemed more liable to occur with the higher currents. In many cases the standard sheath became ignited within a few seconds of the bursting; in most of the other cases the dielectric was converted to a carbonized and conducting red-hot mass. In some instances this became self-ignited, or, if this did not happen, very slight movement of the cable was sufficient to restart the arc.
(2) A standard rubber sheath, whether used in conjunction with standard vulcanized-rubber or fire-resisting dielectric, could be made to continue burning relatively easily, but cables using a fire-resisting sheath were superior from the standpoint of the cable becoming ignited, as they were self-extinguished after the arc ceased.
(3) All four constructions tested on these unscreened samples allowed flame from the arc to reach the atmosphere and thus could have caused a fire in a gassy or " fiery " mine.
(4) It is to be noted that the foregoing results were obtained with currents less than the normal rating, i.e. under conditions where a circuit-breaker based on overload would not operate, whatever the setting.

The fact that under some conditions the dielectric was converted to a red-hot conducting mass, which sometimes became the immediate cause of the cable igniting, suggested that the use of a conducting screen connected to a quick-operating earth-leakage device would prevent either open sparking or ignition of the cable. A few experiments were therefore put in hand to test this idea. In the first place a pre-formed wire braid was slipped over the cable and connected to an earth-leakage trip. A 4-amp. arc was struck between the broken conductor ends, and the ammeter showed that this current was maintained for 1 hour (presumably by the formation of a carbonized mass), although definite arcing was not maintained. The current was then raised to 8 amp. for $1\frac{1}{2}$ hours, during which time repeated attempts were made to produce some fault by hitting the sample with a hammer, but with no visible result, and the earth-leakage trip did not operate. On opening-up the cable it was found that the whole of the dielectric was carbonized in the immediate vicinity of the arc and the sheathing was also carbonized for the greater part of its thickness, but there was still about $\frac{1}{16}$ in. thickness of sound sheath immediately beneath the screen. In other experiments carried out both at 10·5 and 20 amp., the sheath beneath the wire-braid screen did not burst, but gases were forced along the sample, bursting the sheathing at a point beyond the screen. These first experiments therefore showed that screening was an improvement, but it was felt that some of the improvement might be due to mechanical reinforcement, while the cooling effect of the relatively large amount of metal braid could not

be entirely ignored. Further experiments were therefore carried out in which the cable was lapped with tinfoil, over which was slipped a tube of vulcanized rubber. In the first experiment a 4-amp. arc was struck, and after about 5 minutes some smoke appeared and simultaneously the leakage trip operated. There was no visible sparking. A similar experiment was carried out with a 20-amp. arc; the earth-leakage device operated in about 30 seconds, and although there was some smoke there was no visible ignition of the cable or discharge of flame. Had the outer sheath been "continuous" it is doubtful whether even smoke would have made its appearance, and the current would have been cut off without any external evidence of a fault.

From the above experiments it seemed clear that screened cables are safer than unscreened cables from the fire standpoint. However, if there is delay in operation of the earth-leakage trip it is still possible for core-to-screen arcing to occur. These conditions would be similar to those already described, which have indicated that quite small currents of the order of 4 amp. are sufficient to cause pronounced arcing and ignition of a standard rubber-sheathed cable if allowed to persist for even a few seconds. Increase in the intensity of the arc within the limits investigated in the present work does not seem to be more liable to ignite the cable; in fact there are indications that with the higher current density the arc is more liable to be extinguished by the violence of the explosion when the sheath bursts.

The present experiments suggest that any circuit-breaking device connected to the screen and set to operate almost immediately, or at any rate before the outer sheathing has burst, should be effective in preventing fire.

While the Laboratory experiments are probably somewhat fantastic so far as mining practice is concerned, they are important in indicating that serious consideration should be given to the use of screened cable and earth-leakage protection to give the full possible measure of protection.

In particular, the effects of the arc with even small currents are worthy of attention, even admitting that the deliberately maintained arcs are most unlikely to occur under practical conditions of service.

(4) A COLD-SETTING JOINT-BOX COMPOUND

While this new type of compound is not directly associated with fire resistance, it has been greatly discussed in connection with urgent repairs under emergency conditions, and as one of its important features is that its use does not require heating of any kind, and so is particularly safe for gas-laden conditions, it is hoped that a note here and an opportunity for discussing it will not be out of place.

Publication or part publication of the properties of the compound itself has already been made. In view of this, and seeing that the Transmission Section will be concerned almost entirely with the operational aspect of the material, this note can well be confined to new matter, excluding the question of chemical composition of the compound.

The use of a cold-pouring and cold-setting box compound was first considered some years ago in connection with low-voltage boxes used in collieries and similar places where it is inadvisable to use lamps, etc., for heating the normal pitch compounds. Although the use of such compound has been somewhat limited it is understood that it has been satisfactory for this type of service.

For high-voltage work in normal times the standard pitch compounds have such extraordinarily good qualities that it is hardly necessary to look for alternatives. Probably their only drawback is the time taken to fill and re-top a joint owing to the contraction of the compound on cooling, and the need for slow cooling and topping-up to avoid cavities.

The present abnormal times, however, and the extreme need of jointing cables and putting them into service in a very short time, with the additional complication of a possible gas-laden atmosphere, called for urgent investigation of the cold-pouring and cold-setting compound for repairs to high-voltage cable under emergency conditions, and it was found that in a suitable box or sealing-end it was wholly satisfactory as a sealing medium.

The main operational characteristics of the compound are as follows:—

(1) The setting properties of the compound are brought about by the interaction of two materials which are mixed only just before it is necessary to pour the compound.

(2) As the compound is fluid until after it is poured, it does not require heating in any way before pouring.

(3) The breakdown voltage, although not so high as that of pitch compounds, is amply high for emergency joints. Actually a reasonable acceptance test for the material is 25 kV applied for 1 minute across the standard $\frac{1}{2}$-in. spheres set at a gap of 2 mm.

(4) The compound does not change in volume to any appreciable extent during the setting process, and therefore it is not necessary to top-up in any way.

(5) After setting, the melting point of the compound is about 55° C.

The setting time of the compound and the final hardness may be varied within considerable limits by slight modification of the two constituents, and while agreeing that these properties may well be left to the individual firms interested in one or other of the three or more types of compound now available, it may be stated that as a minimum a compound of this type should not set in less than 20 minutes after the start of mixing, this giving time for filling the joint, and after 24 hours it should have set hard. After this time the compound continues to harden for a week or two. A typical case, the figures on which are not necessarily applicable to all types of this compound, is illustrated in Fig. 11 (Plate 4).

Out of the very large number of laboratory tests made to prove the quality of this compound for this particular type of service, one may be quoted. Eleven 3-core 11-kV joints were inserted in a 250-yard length of cable. Four of the joints were filled with standard hot-pouring box compounds and the remaining seven with cold-filling compound. All joints were subjected to a 3-phase voltage test of 33 kV, current heating cycles being applied

at intervals throughout the test. After prolonged application of the voltage, deterioration of the dielectric of the hot-filled joints could be detected. No such deterioration, however, appeared in the cold-filled joints, neither did these latter joints show signs of being affected even after many hundreds of hours of the treatment.

To quote another example, a 66-kV temporary emergency-type joint and terminal were subjected to a step test the details of which are given below.

kV to earth	Joint	Terminal
	min.	min.
60	30	30
70		
80		
90		
100		
110		
120		
130		
140		
150		
160		
170		
180	12 (breakdown)	
190		
200		Limit of testing transformers

An illustration of the joint tested is given in Fig. 12 (Plate 4).

One of the principal requirements of a box compound is that it shall effectively exclude moisture from a joint, and in the course of the development of the cold-filling compound many of the experimental products were tested by immersion in water over a period of many months in order that the resistance to water might be increased to a maximum. Joints filled with the new compound have also been immersed in water, and after many months, with a 500-volt d.c. supply connected to the cable cores, no measurable deterioration of the insulation has been recorded.

Cold-filling compound was originally developed for use with paper-insulated cables, but tests have been carried out which show that the compound is equally satisfactory when used with rubber-insulated or vulcanized-bitumen-insulated cables. Other experiments have shown that a joint box can be filled whilst the cable is alive.

Numerous other experiments have been made to ascertain the qualities of cold-pouring compounds, such as adhesion, etc., and temporary joints were made in one of the grid lines operating at 33 kV some months ago and have been in continuous operation ever since without trouble of any kind.

In this particular instance the straight-through emergency joints made in 6 hours from start to finish, and housed in wooden boxes, were buried direct in the ground without other special protection, and the voltage was applied immediately the joints were complete. The fact that the joints have for some months withstood all reactions of weather, loading, etc., is good practical proof of their effectiveness.

While all experts will probably agree that for the great majority of cable-jointing jobs under normal conditions the standard pitch compounds are unsurpassed, it is clear that for certain other conditions and some types of use the cold-pouring and cold-setting compounds have a definite and important field.

(5) ACKNOWLEDGMENTS

The author's thanks are due to the Cable Makers' Association for permission to publish all the results which the paper contains.

Thanks are also due to Mr. J. A. B. Horsley, O.B.E., late Chief Electrical Inspector of Mines, for the initiation of, and the matters described in, Section (3) of the paper, and for his keen interest and help in the work.

DISCUSSION BEFORE THE TRANSMISSION SECTION, 13TH MARCH, 1940

Mr. H. Nimmo: I am surprised to find that many engineers are slow in making use of the recommendations drawn up by the Fire Risks Investigating Committee of the Electricity Commission. For example, a short time ago I was looking at the back of a switchboard where the main cables were covered with one layer of asbestos tape, and the control cables, which ran parallel to the main cables and quite close to them, were not covered at all. The Fire Risks Committee recommended that the control cables should be given the same degree of protection as the main cables.

Section (1) of the paper is headed "The Fireproofing of Main Cables in Power Stations." Does this title cover the control cables as well? I think it is really more important to protect the control cables than to protect the main cables; because if the control cables are properly protected there is a good chance that the protective gear will come into operation and save the situation.

In the same Section of the paper the author states that he favours the use of moulded asbestos for fireproofing purposes. It would be interesting to know whether gypsum, which seems to have very good heat-resisting qualities, has been tried for this purpose. Last year I attended a test conducted under the auspices of the National Fire Brigades Association, on a 3-in. partition wall made of gypsum blocks. A number of gas-fires were playing on the enclosed side of the wall, while the other side was exposed to the atmosphere. The test lasted for 1 hour, and the result showed that such a wall would withstand a maximum temperature of 927° C. On the side exposed to the atmosphere the temperature did not exceed 130° F.

On page 522 the author makes the assumption that the main problem to be faced, so far as cables are concerned, arises from extraneous fires due to the flow of burning oil; but I would recall that in the Bradford disaster there was no conclusive evidence that any oil reached the basement of the station. Burning cables slipped through the switchroom floor into the basement and set fire to others, which reduced the whole cable system there to 30 tons

of scrap copper and 9 tons of lead. The cables were carried on brackets fitted underneath the ceiling of the basement where there was free access of air. It was observed that those cables which were taken down to a trench in the floor of the basement were not burned at all to an average height of 6 in. from the floor. Above this level the whole of the insulation and lead had been burnt off. The conclusion I have drawn is that cables with good air circulation will burn freely but cables on a shelf or on the floor will not burn unless burning oil or bitumen is there. It would be interesting to have the author's views on these points.

I notice that the rubber-insulated fire-resisting and self-extinguishing cables described in Section (2) are restricted to the sizes and types of cable normally used in ordinary wiring work. It would be valuable if the same principles could be applied to lead-covered paper-insulated cable. It was estimated that had the cables in the Bradford station basement been self-extinguishing, 70 per cent of the total Bradford supply would have been restored the day after the fire, instead of only 15 per cent. It took 8 days to restore the complete supply.

The investigations described in Section (3) are mainly of interest to mining engineers: but in view of the vulnerability of lead-covered paper-insulated cables it might be advisable to use mining-type cables in generating-station basements. I am impressed by the statement that steel armouring provides a substantial degree of fire-resisting qualities; how does it compare with steel-tape armouring in this respect?

Mr. J. A. B. Horsley: Following the explosion and fire at Gresford colliery in 1934, when some 265 lives were lost, mining engineers became seriously alarmed about the subject of fire risks in general. In particular, some of them were afraid that electrical cables might carry a fire, once started, throughout the length of the roadway.

The following figures relating to fires which have occurred in mines in this country are of interest. During the 20 years from 1919 to 1938, 1 675 fires were reported, most of them of no serious consequence. Of that number 84 were attributed to electricity, 868 to spontaneous combustion and 723 to various other causes, including a number due to mechanical friction in haulage gear and conveyor machinery. An analysis of the electrical fires shows that 26 involved flexible cables, 28 armoured cables and 8 other types of conductors (single-core unarmoured cables used as interconnections, etc.).

There are to-day in this country more than 1 200 000 h.p. of electric motors below ground, and about 10 000 electrical coal-cutting machines and electrically driven conveyors are in use. Associated with these coal-cutting machines and conveyors there are some 1 000 000 yd. of the flexible cable with which the paper is concerned.

Fractured cores have been the cause of several fires in flexible trailing cables. In some cases one conductor was broken while the trailing cable was in use, and the arc due to load current ultimately set the cable on fire. There have been several instances where a coiled-down flexible cable has been set on fire by the arc due to an electrical defect and the flame spreading upwards has destroyed the whole coil.

The screened flexible cable adopted in mines as a safeguard against shock requires for the completion of that safeguard the use of reasonably sensitive leakage protection. I am interested to learn that the author's experiments have convinced him that the screen increases the fire-resisting power of the cable. Of the total of 26 electrical fires involving flexible cables, in 7 instances screened cables were in use.

With regard to armoured cable, I submit that for shafts double-wire armouring is essential and that in roadways it is always to be preferred.

I am particularly interested in the cold-setting joint-box compound, because the use of hot compound presents difficulties in a mine. There is first the question of distance; secondly, the impossibility of heating the compound on the spot; and thirdly, the great difficulty of ensuring that the boxes into which the compound is poured are in a proper condition to receive it, as regards the surface deposit of moisture.

Mr. S. R. Siviour: In stating that very little serious consideration was given to this problem before 1937, the author apparently has in mind the more comprehensive consideration of the problem—that is, relating to plant and apparatus. I would remind him that some undertakings did a fair amount of detailed work on cables 2–3 years before 1937, including work on one of the types mentioned in this paper.

The split-moulded asbestos protection to which the paper calls attention seems to offer effective service but is not adaptable to those cases where the runs are not straight.

The author refers on page 522 to a method of fire protection which is particularly suitable for existing installations, and I should like to explain how this has been applied by the Yorkshire Electric Power Co. We protect the cables with two layers of 2 in. × $\frac{1}{8}$ in. asbestos tape, and then apply a waterproof silica paint to fill any interstices and give the tape a hard and smooth finish. The tape extends well into the mouth of the conduit. It is essential that the asbestos tape and silica paint should be free from alkalis harmful to the lead sheath. This type of protection was subjected to a severe test some 2 years ago when a fire broke out and about 40 gallons of oil were released on the bursting of a switch tank. The cables were enveloped in flames for a period of 20 minutes, but afterwards when we stripped the tapes off the lead sheath we found it was not even discoloured.

The chief use of the manufactured type of protective cable mentioned in the paper is for long runs in cable basements and tunnels. In these cases the runs are never straight and there would be difficulty in applying the external form of tubular shield, which in addition would be very costly. There would be a wide field of use for an economical manufactured type of protected cable. In order to use such cable for terminating into substations it would be necessary to insert a joint outside, which would be costly.

I notice that most of the tests referred to in the paper consist of on and off periods of 15 to 30 sec.; but longer tests, of 20–30 min., are necessary to simulate the conditions which occur when the fire is spread over a greater area.

Dr. P. Dunsheath: I should like to place on record the fact that the contents of this paper represent only a small fraction of the work which has been carried out by

the members of the C.M.A. in investigating this very important question. For instance, the author has not been able to deal with the fundamental question of laying down a standard test for comparing the results of the experiments which have been carried out. That work in itself brought to light many interesting phenomena, such as the vital effect which a slight draught has on the inflammability of a cable whose fire resistance one is trying to determine; also the difference between cables tested in a vertical position and in a horizontal position. These and other similar questions had to be cleared up quite early in the investigation.

It might be worth while asking ourselves why it is that when we take a number of very inflammable materials and combine them into a cable, the cable itself is nothing like so inflammable as its constituent parts. I think the answer lies principally in the fact that the cylindrical form of the cables does not offer a very big surface to the air. This view is supported by the evidence of Mr. Nimmo that the spread of the Bradford fire was favoured by the existence of a number of cables with no barriers between. Thus we see that the disposition of the cables is an important practical question. Another factor is the ease with which the heat is carried away longitudinally by the metallic components of the cable. The transmission of heat along the conductor and armouring holds down the maximum temperature at the point where the burning is taking place, and so prevents volatilization of the organic material.

As regards the rubber cables referred to in the paper, the inclusion in the rubber mix of mineral ingredients not only reduces the amount of volatile material there, but also increases the thermal conductivity, and so again facilitates the cooling of the cables.

In explaining one of his slides the author mentioned the danger of inflammable material (e.g. rubber, paint, compound) dropping from the cable on to other inflammable material which may be lying beneath, and so spreading the fire along the cable. This difficulty has been largely overcome by the adoption of the special fire-resisting compound.

The paper refers almost entirely, as regards rubber cables, to the use of one synthetic material, but before this material was adopted as standard many experiments had been made with a number of other materials. Although many had excellent properties they were discarded for various reasons in favour of the one type.

Even now, finality cannot be claimed, and cable makers will naturally continue to explore for a long time to come the various new alternatives as they become available.

Mr. F. H. Sharpe: I propose to confine my remarks chiefly to Section (1) of the paper.

The disastrous event preceding the issue of the recommendations of the Electricity Commission immediately led to an unfortunate swing of the pendulum, and I saw fearsome apparitions in the many stations into which my duties take me. Where cables had not taken on a mummified appearance from their swathes of asbestos tapes they were entombed in various mixtures, mostly containing asbestos. These might, in many cases, be described as death masks because the majority of cement-asbestos mixtures would shatter under intense heat. Asbestos materials are costly and the expenditure must have been considerable: some of the money might have been better spent in other ways, e.g. rearranging cable routes and the provision of fire-fighting equipment.

This argument also applies to new work—the various fire protective materials, including armouring (with the helpful effect of which I agree), increase cost considerably, both directly and indirectly, by reducing current capacity. Sound layout and segregation with fire-fighting equipment commends itself more to me, except that protection is necessary immediately adjacent to the switchgear with its oil risk. The large plant capacity in use to-day introduces severe cabling problems, and we can ill afford a 20 per cent reduction in rating. Are the split tubes filled with air, compound or sand? In practice they cannot be maintained in close contact with the lead.

My experience of ordinary waterproofing is that initially it affords quite a measure of protection to the lead—in fact, until the volatile gases have been driven out of the bituminous compounds in the tapes. After that the gases and the dripping compound feeds the fire. The type of finish suggested on page 522 should prove more attractive than the normal waterproof covering if (*a*) it does not cost much more, (*b*) it is not materially less waterproof, (*c*) it does not materially reduce the current capacity, (*d*) it does not contain highly volatile bituminous compounds. Can the cable industry to-day meet these conditions?

It is not always easy to make a clear-cut decision between indoor and outdoor work. A universal covering is wanted, particularly for the most difficult case of cables laid on posts along railways, which are subject to fire risk but also require adequate waterproofing.

Some particulars of tests made in an attempt to reproduce a cable fire on such a route may be of interest. After a number of fires had been made and extinguished, with interesting results, a thermite bomb was ignited between the battens supporting the bottom two cables of a total of five, all of which were similarly run on concrete posts with cement-asbestos sun-screens. There was a short and vicious fire, which went out of its own accord 1 minute later. We presumed the bitumen had previously been consumed, and we had already proved that the battens themselves were not easily set on fire. The test was repeated on a section which still had plenty of free compound in the waterproofing: a good fire resulted. Our general conclusions from these and the several preceding tests were: (1) Care must be taken to avoid an arrangement of cables and supports which may give a chimney effect. (2) An ordinary grass fire does not readily set fire to such a cable installation unless there is inflammable rubbish about, or excess waterproofing compound has exuded on to the battens, grass and any rubbish which may be at hand. (3) Battens themselves do not constitute a severe risk, but may act torch fashion. (4) The immediate vicinity of the cables should be cleared of grass and rubbish (which collects there because of the wind) and treated with weed-killer, which is quite cheap and effective. (5) The waterproofing must be of a type which is not readily fired and which is free from volatile gases that, once fired, instantaneously turn a smouldering hessian into a flaming torch. Is there such a waterproofing tape available at a reasonable price?

Dealing with other detail points in the paper, I endorse

the warning against the use of sand. It collects oil, which in turn soaks into hessians and is generally rather messy, apart from reducing thermal rating in a congested cable trench. Where chippings are used, care should be taken to rake them up at intervals so as to prevent packing.

Having some experience of mineral-insulated cables, mentioned in Section (2), I admit that one tends at first to cling to the more easily handled rubber cables. There is, however, nothing very fearsome in the technique of the use of the mineral-insulated cable; unquestionably it is the ideal fire-resisting cable, and has surprising mechanical strength. Consequently it should be used at least for emergency lighting or communication circuits, for main tripping d.c. supply mains, and other services falling in this category.

Is any information yet available about the cost of synthetic rubbers? Their qualities are most attractive.

I am glad that in Section (3) the author makes an important point in relation to all fire questions—that the supply of electrical energy should be cut off as soon as possible. Earth-leakage relays for work underground sound very attractive in this connection.

Mr. G. O. Watson: I am disappointed that the author does not devote more space to fires in ships and in buildings. We have been fairly free from major fires in ships, probably because of the care which we take in installing our cables. Nevertheless, there is a number of small fires which do not, perhaps, always come to the notice of the public. To take the electrical installation of a typical luxury liner accommodating 1 300 people (including the crew), the generating plant will be of about 3 000 kW, and there may be over 400 miles of cable, 20 000 lamps, 400 motors, 650 fans and 5 000 fuses. All that equipment is confined to perhaps 500 ft. length of hull, and to utilize so much power in such a confined space requires a multiplicity of small cables in groups or bunches, and this constitutes a serious fire risk.

The "Rules for Electric Propelling Machinery and Rules for Electrical Equipment," issued by Lloyd's Register of Shipping, do not allow the use of tough-rubber-sheathed cables, as they mean the presence of a large amount of inflammable material. Fires can start in these cables by arcing across exposed ends, by fuses falling out of their clips, and by overheating of socket-outlets.

Arising from Dr. Dunsheath's remarks on the transmission of heat by cable conductors, we find that if a fire breaks out on one side of a fireproof bulkhead the heat is conducted through to the other side, where it often starts another fire. Therefore, in all large ships such as the "Queen Elizabeth" and the "Queen Mary," we take special care that where cables pass through a fireproof bulkhead a box construction is built round the cables and filled with heat-insulating material. This retains the heat in such a way that the outer surface of the box is kept cool.

It is rather disappointing that the author does not say what tests are being applied to the cables mentioned in Section (2) to demonstrate their fire-resisting qualities. These cables are necessarily of lower insulation resistance than the ones we used in the early days. The values of 2 500 or 600 megohms which were common then were attained by using a large amount of pure rubber, and this has since been found to be undesirable. It would be interesting to have a comparison between the insulation resistance of these fire-resisting cables and that of the cables which are at present in use. Have any mechanical or ageing tests been carried out on these new rubber cables to show whether they will last as long as the present standard types?

The few tests described in the paper seem to me to be of the wrong type. Most of the author's illustrations show the cable in a horizontal position, whereas a vertical cable is more likely to spread the fire once it is well alight. According to the description on page 526 of tests on flexible cables, these were laid on a concrete bench; surely this would tend to keep the cables cool and prevent the air getting to them. Another test which could be applied is to pass an overload current of 5–10 times the normal current and thus fire the cable from inside. My experience of "fireproof" cables has been that if the conductor is overheated in this way the outer covering prevents escape of the volatile gases and then the cable suddenly bursts.

Mr. E. G. Cawte: Two conflicting factors enter into the problem of the protection of cables against fire by covering them with asbestos or other material. On the one hand a high thermal conductivity is required so that the cable does not heat up, and on the other a low conductivity seems to be necessary to prevent the heat reaching the cable through fire. These requirements are not really incompatible. As far as the generation of heat within the cable is concerned, when the steady state is reached all the heat that is produced in the cable is lost from it to the air. On the other hand, heat applied from outside cannot escape once it has got into the cable, and it is only a matter of time before the whole cable reaches the external temperature. Where, as in this case, time enters into the problem, the determining factor is the diffusivity, i.e. the thermal conductivity divided by the thermal capacity. Now asbestos, in the form used for the protection of cables, has a moderate conductivity and also a fairly high thermal capacity; consequently it gives a long protection time without overheating the cable. Chemical change—decomposition—can absorb heat and thereby delay its passage through the material. Asbestos, in common with most materials used for fire-protection purposes, undergoes some degree of decomposition on strong heating, but this does not materially affect its mechanical strength.

Mr. Nimmo referred to a test in which one side of a gypsum wall was strongly heated for 1 hour, in which time its other surface only reached 130° F. This result was what might be expected, but it would be a mistake to infer that it would apply to cable protection, as the two cases differ fundamentally.

Mr. B. Donkin: Section (2) of the paper describes the development of synthetic insulating materials having characteristics similar to those of rubber insulation but having self-extinguishing properties. The author states that the synthetic material whose electric strength is comparable with that of rubber has such a low insulation resistance that it cannot be used alone as an insulating material for general wiring work. The insulation resistance of the complete wiring installation is almost entirely dependent on the number of cable terminations and

terminal points, the quality of the insulating material being a relatively unimportant factor. Therefore, unless the use of a material having low insulation resistance increases the surface leakage across the ends of the insulation out of all proportion, self-extinguishing and fire-resisting properties could, and I think should, be achieved at the expense of a reduced insulation resistance.

In common with some other speakers I should have liked to see more of the author's tests carried out with cables arranged vertically, as this is the most usual arrangement of cables leading to switchgear and transformers in generating stations and substations. The data obtained in these laboratory experiments are interesting because they agree very closely with the results of a fire which occurred about 3 years ago in an important 33-kV switch station in the N.W. England area. The failure of a 33-kV switch caused large quantities of burning switch oil to spread over the floor of the switch-house. The explosion resulting from the switch failure blew out most of the doors and windows, and hence there was plenty of oxygen available to feed the fire. This was extinguished, however, as soon as the portable fire-fighting equipment had been brought effectively into use. In the substation connected with the switchgear there was a number of 33-kV single-core cables, some of which had the usual waterproof serving over the lead sheath. After the fire had been put out it was found that in the case of four of the cables whose sheaths were bare the sheaths had been melted in places, exposing the paper insulation; whereas the cables with the usual waterproof serving consisting of impregnated hessian had not been damaged at all. This shows the excellent heat-insulating properties of comparatively thin layers of the usual waterproof serving. No great advantage is to be gained by providing a large amount of heat insulation such as would withstand a high temperature for a considerable period, because a fire of that nature would in all probability destroy both the switchgear and the building. In the past it has been common practice to strip off the waterproof serving of the cable where it runs inside the building; this was probably done for two reasons—firstly, that of appearance, and secondly, with the idea of reducing the fire risk. But the author's experiments and the experience to which I have just referred show that waterproof serving should be left on, but that steps should be taken to make this serving as fire-resisting as possible without appreciably increasing either its thickness or its cost.

Section (4) of the paper deals with the cold-setting joint-box compound. In the construction of these temporary joints the cold compound is used both as an insulating material and as a means of sealing the joint so as to exclude moisture. I should be glad if the author would say whether when the cable's maximum temperature is reached, and if the compound is liquefied, there is risk of failure of the joint at this point.

Mr. W. B. G. Bonsey: I wish to speak about Section (2) of this paper, and in particular with reference to cables having mineral insulation.

I am surprised that when discussing fire-resisting cables the author does not deal in detail with the one type of cable which is completely immune from fire risk; the reasons given for not doing so, being that such cables require special attention in respect of sealing the cable ends and that they tend to be rigid, which makes the installation of the cable difficult. The manufacturers of such cables are able to state that a period of 2–3 hours' instruction only is required in order to guarantee a perfect installation by the average electrician. While on this point I should like to say that no cable failure would be experienced even if the cables were unsealed when installed. No carbonization or tracking takes place should leakage currents pass through the mineral insulation.

Referring to Mr. Watson's remarks, it is interesting to recall that fires experienced by the French marine authorities led to the initial development of mineral-insulated cables in that country.

Mineral-insulated cables survived a fire which took place recently at a factory in Leeds. The fire was caused by the overheating of a boiler flue, which caused a timber roof to ignite. The cables were tested after the fire by officials of the Leeds Corporation Electricity Department, who found no circuit of the installation with an insulation-resistance test less than 100 megohms. The only damage to the cable which occurred during this fire was caused by falling debris, which broke an insulating ferrule.

In conclusion, I would remark that although objections are raised in connection with the installation of mineral-insulated cables, the sacrifice of 2 hours of an electrician's time in acquiring knowledge of the characteristics and installation details of this type of cable is surely worth while when the use of a truly fire-resisting cable is essential, and such a cable is available.

Mr. W. S. Lovely: There is just one point to which I should like to refer, namely the nature of the fireproof serving which is applied to cables.

Cotton tape is recommended as an overall serving to improve the finish of the cable, but from a number of tests in which I have been interested I have come to the conclusion that such cotton tape serves a much more important purpose. I have found that the close texture of cotton tape is the determining factor in the success or failure of such serving. If one uses normal open hessian, impregnated, the hessian can never be very well impregnated and rapidly burns away, leaving little piles of fireproof compound in the interstices. A closely woven cotton tape does not show this feature, and stands up to fire conditions for very much longer than hessian.

My experience, like that of many others, is that cables are not in themselves fire generators. Cable fires occur when compound is dripping from them, and generally not until then.

I prefer the moulded tubular to the tape type of fire-resisting installation. Tubular material, if it is assembled with only one joint (which should be a long vertical one, uncemented and wire bound), is quickly removed, and with such an installation one can get to know the state of the cable much more quickly than if one has to unwind a lot of taping. Tubing should be held together by a wire bond which has a melting temperature higher than any that is likely to be encountered in service.

Mr. S. W. Melsom (*in reply*): Regarding the points raised by Mr. Nimmo; first, the control cables should, of course, be protected as are other cables, and if the control cables are of small diameter comparatively simple methods can be used to give a large measure of protection.

The alternative to moulded asbestos should, as far as I can judge, be well worthy of further investigation. The evidence as to fire-resistance is complete, but it would be interesting to know the thermal resistivity of the material.

As to the difficulty evidenced by the Bradford fire, there seems to be little doubt that, if any one of the methods of protection outlined here had been used, the cables would not have caught alight and so helped to spread the fire.

Regarding the suggestion that rubber-insulated and fire-resisting self-extinguishing cables might be used in preference to paper-insulated cable, it is to be expected that the use of these cables for incoming leads from the main cables to the switchgear, etc., will be fully considered both from the point of view of cost and also as regards degree of immunity from fire. At the moment it looks as though the protected paper-insulated cable will hold the field.

The possible interaction between mining practice and power-station installation is interesting. While steel-tape armouring will undoubtedly provide a fair degree of resistance to fire, it is unlikely that it will be nearly so good in this respect as steel-wire armouring.

Mr. Horsley's remarks are invaluable in consideration of a paper of this kind. The flexible trailing cables used in mines are nearly the most difficult cables to design if they are to have a long life under the prevailing conditions of service, but it is hoped that the intensive development work which was going on immediately prior to the war will result in a distinct improvement. Mr. Horsley mentions the coiled-down cable, a particularly difficult condition which apparently has to be met in coal-mining practice. The current rating of the cable is, of course, based on the free-air condition, and when, as often happens, a large proportion of the cable is coiled-down, the coiled-down section is bound to become overheated.

I agree with Mr. Siviour that quite a fair amount of work had been done before 1937 on the fireproofing of cables. This work was done in collaboration with various engineers, of whom Mr. Siviour was one, and resulted in the evolution of one of the methods mentioned in the paper.

The manufacture of the special type of protected cable mentioned naturally creates difficulties, since this type of cable would not be suitable for laying direct in the ground owing to the fact that the normal protective compounds are omitted. Therefore, it might be necessary to have a joint immediately inside the substation, which might be considered undesirable. Just one point, however, regarding these long runs in cable tunnels: surely quite a fair degree of fire resistance could be obtained if the tunnels could be shut off.

Replying to the point as to the period of the fire-resistance tests, these particular tests were made on small cable, and a period of from 15 to 20 sec. was probably the most severe condition. I agree that for large cables the period should be longer.

Replying to Mr. Sharpe, cables having the type of finish suggested on page 522 are intended for indoor service and would not be suitable for laying direct in the ground. It is, of course, unfortunate that the ideal materials for providing protection against water and soil-corrosion burn freely, and that, so far, a material that would give complete protection against both corrosion and fire has not been found.

Mr. Watson draws special attention to the importance of ships, and one cannot fail to agree with him. It is to be hoped that the new type of fire-resisting cables will be especially useful in ships' installations, particularly where a multiplicity of small wires has to be installed in a confined space. In fact, it is hoped in the near future to submit these cables for the rigid tests and the formal approval which is necessary before they can be used on ships. It is somewhat surprising to learn that the fire-proof bulkheads in ships do not wholly prevent the transmission of fire from one bulkhead to another, and it is at least likely that, if these new types of cables were adopted, the special precautions at present necessary would not be required.

On the question of the method of testing the fire-resisting qualities of these cables, raised by both Mr. Watson and Mr. Donkin, the great majority of the illustrations of the test methods refer to mining cables where, in order to simulate service conditions properly, the cables were laid horizontally. Fig. 1, however, does refer to a vertical run of the fire-resisting cable, and shows on the right-hand side an ordinary rubber core and on the left-hand side a fire-resisting core. All the tests of the fire-resisting cables were made with the cables in a vertical position, and the tests were devised so as to be of the most extreme nature possible.

As to the values of insulation resistance, the values for the new dielectric are about one-third of those obtained with standard vulcanized-rubber cables. Even so, this amount is so high that it would not affect the total insulation resistance of a circuit comprising a number of switch and other points.

Both mechanical and ageing tests have been carried out on the fire-resisting rubber cables; in fact, all sorts of tests have been carried out during the last 3 or 4 years on these cables with results which have invariably been comparable with, or better than, those for standard rubber cables, with the possible exception of the value of insulation resistance. The additional test suggested by Mr. Watson of heavy overload current through the conductor, with the possibility of firing the cable from the inside, will be made. I have little doubt as to the result, but in a matter of this kind it is essential to prove everything by suitable tests.

Mr. Donkin discusses the question of insulation resistance, and I am wholly in agreement with him. At one period a measurement of insulation resistance was practically the only criterion of cable quality—in fact, cables were graded on the basis of their value of insulation resistance on the assumption that the higher value meant a better cable—and tradition dies hard.

As mentioned in the reply to Mr. Watson, the insulation resistance of these cables is very much lower than that of standard cables. Possibly a better result from the point of view of fire resistance might have been obtained had the whole of the dielectric consisted of fire-resisting compound, but there is little doubt that this would have resulted in such a low value that it might have been an important factor in the case of a large installation. Mr. Donkin's experience showing the value of the fire-resisting serving is most interesting. I have no

doubt he will agree that, if this fire-resisting serving had been served with a special cement to render it wholly non-inflammable, the result would have been even better.

In reply to Mr. Donkin's question as to the temperature limitations with cold-pouring compound, the joint box is usually cooler than the cable run, and generally it is expected that the compound will be suitable for cables operated up to their normal maximum temperature.

I am sure that Mr. Bonsey has dealt with the question of mineral-insulated cables very much better than I could have done. These cables undoubtedly have a useful, if limited, field. While I have no first-hand experience on the question of leaving the ends of this type of cable unsealed, I am doubtful as to the accuracy of Mr. Bonsey's statement. In my opinion, if the ends were left unsealed permanently or for any considerable time, the moisture from an atmosphere having a humidity such as is normal in this country would result in an intolerably low insulation resistance.

Mr. Lovely mentions the question of cotton tape as compared with the more open-texture hessian tape; this is an interesting point, which will be further investigated.

DISCUSSION ON "FIRE-FIGHTING EQUIPMENT FOR ELECTRICAL INSTALLATIONS"*

EAST MIDLAND SUB-CENTRE, AT LOUGHBOROUGH, 9TH APRIL, 1940

Mr. B. C. Bayley: Of all classes of fires the ones which are most dreaded in the electrical industry are those in which oil is involved; the rapidity with which they spread, and more particularly the amount of black smoke which is given off, render control with portable appliances, such as the CO_2 type, very difficult, if not impossible.

Engineers responsible for expensive electrical plant, such as large transformers and h.v. switchgear, when deciding the medium to be used for giving protection from fire hazards must weigh the balance between damage to the plant by the extinguishing agent and damage by fire. In recent installations for which I have been responsible the layout and construction of the buildings were such that a gaseous medium was ruled out on account of the ventilation provided for normal running, and the risk that in the event of an explosion unforeseen damage might be done to the building, which might result in the gas plant becoming ineffective. Foam installations need very careful designing, and the after-effects of foam deposit are difficult to deal with, delaying the restoration of supply. For the average installation, either indoor or outdoor, the third medium—water—is the most suitable, for in the event of explosion and damage to the building it is the least likely to be put out of action. I am thinking of the fixed system which, on coming into action, bombards the oil with an emulsifying spray evenly distributed and discharged at high velocity from specially designed nozzles. This system must not be confused with the ordinary type of sprinkler installation, which would merely tend to spread the fire.

I am somewhat disappointed that the paper does not include any data on switchgear protection. I have recently been responsible for installing this emulsifying system over ironclad-type h.v. switchgear, and in order to minimize the risk of the complete switchboard being put out of action the installation was sectionalized, a small group of projectors being connected to each control, in the hope that if the fire could be localized only a section of the installation would come into operation. To eliminate risk of water leakage from the fittings or pipe joints, it is advisable to avoid placing them over the electrical gear. Where this has been incompatible with proper protection, we have introduced air under pressure into the pipe-line so that no water can reach the gear unless a control operates.

There is another very important aspect of the present situation to which we have given careful thought, and that is whether with such fire-fighting equipment installed over indoor-type apparatus, which is not watertight, if a bomb were dropped in the vicinity from hostile aircraft the shock or blast would cause a control to operate. As the manufacturers are not prepared to express a definite opinion on this point, we decided to take the precaution in some cases of making the installation semi-automatic by closing subsidiary hand valves, the installation being so arranged that in the event of a fire a visual and oral alarm would be given, and the attendant would then use his discretion as to whether to open the water valves. This arrangement applies to regularly attended substations.

I realize that there are two schools of thought on this point and that each case must be considered on its merits, but if a fire-fighting installation such as I have described were to come into operation other than owing to a fire, it might result in a long shutdown as compared with the little extra damage that a fire might cause on account of a short delay in opening the valves.

Mr. J. A. Broughall: Fixed apparatus for the automatic protection of transformers being costly, it is evident that whilst it may be worth while to install it for the protection of each transformer, it will rarely be worth while to do so on small transformers. The cost of the apparatus, although not independent of the size of the transformer which it is protecting, appears to be only slightly less when the transformer is small.

As regards small transformers the better plan appears to be to spend some part of the money that might have

* Official communication from the British Electrical and Allied Industries Research Association (see *Journal I.E.E.*, 1939, **85**, p. 719).

been spent on fixed fire-fighting apparatus, on the transformer and the switchgear protecting it, and thereby practically eliminate the risk of fire. Under present conditions this procedure ignores the possibility of the transformer being set alight by incendiary bombs, but this is a special aspect of the matter which does not fall immediately within the purview of the paper.

The authors attach a good deal of importance to the correct positioning of the proposed dwarf wall around a transformer. It appears to be well worth while to confine the oil by means of such a wall, and the advantage of doing so is one which can be secured at a relatively low cost. The position of the wall appears to be of some importance, and the views of the E.R.A. on this subject would be welcomed. The wall cannot of course be arranged to collect with certainty oil spurting from a tube, and from this point of view it is fortunate that the protection necessary for A.R.P. reasons involves a high wall.

As usual, a compromise solution has to be adopted in each individual case, taking into account the relative cost of the transformer and of the protective equipment, the likelihood of fire developing, and the loss of revenue and damage to adjacent equipment if it should do so.

Mr. B. Nuttall: My experience has been largely confined to the fixed automatic Mulsifyre system. This system uses water projected at a high velocity so that it impinges on the surface of the oil in the form of a dense mist. In one case of which I know, a large outdoor power transformer and surrounding property were saved from serious damage by the prompt operation of this apparatus, the fire being automatically extinguished long before the arrival of the fire brigade: moreover, owing to the cleansing action of the jets and the drainage arrangements provided, practically no cleaning-down was required. When the installation was designed, the use of a dwarf wall was considered but this idea was discarded in favour of high walls on three sides, for the following reasons: (*a*) The station was close to a public highway. (*b*) This arrangement gives the maximum protection to adjacent transformers, bearing in mind that fires of this nature are usually *preceded* by an internal explosion. (*c*) This arrangement gives the maximum protection against bomb splinters. (*d*) This arrangement gives support to the cables and, incidentally, to the detector and projector pipework of the fire-fighting apparatus.

The water pressure of the town's main has to be approximately 60 lb. per sq. in. in order that a minimum pressure of 50 lb. per sq. in. may be available at the projectors, to ensure complete quenching of the fire. This is borne out by the author's experiments. It is not uncommon to find the town's pressure below this figure, especially on rising ground. In such a case this system becomes expensive, for it is then necessary to provide an automatic booster pump with suction tank or, alternatively, a pressure storage tank, with hand-controlled motor-driven pump.

For outdoor use the detector system is pumped with air at about 25–30 lb. per sq. in., usually once a week, the water only being released from the double-acting valve in the "frostproof" control house when the air pressure has been released automatically or by hand for testing purposes.

I should like to ask the authors what chemical change (if any) takes place as a result of contact of CO_2 with burning oil, especially when the CO_2 is applied indoors. It seems to me that the CO_2 together with air will be swept upwards in a hot state towards the ceiling, and may liberate free oxygen, which together with hydrogen and methane liberated by the oil, may produce an explosive mixture with the prospect of a secondary explosion.

It was evident from the E.R.A. film that methyl-bromide vapour has a high density, and I understand that for fire-fighting purposes methyl bromide is ejected in liquid form under a pressure of nitrogen. I am interested in the use of methyl bromide for dealing with a fire in a confined space, such as a cable trench, where the man operating the extinguisher has to get down to floor level and is subject to the toxic effects of the methyl bromide. How long could one stay in such an atmosphere without experiencing harmful effects?

I do not think the paper stresses sufficiently the danger due to the spreading of blazing oil. The E.R.A. film showed that it is a relatively easy matter to extinguish blazing oil in a container, where the surface in contact with the air is small compared with the total volume of oil involved. I noticed that at one stage during the experiments the blazing oil spilled over the dwarf walls and was extremely difficult to extinguish. The lesson to be learned in practice is that one should take every possible measure to prevent the flow of oil, i.e. restrict the available surface to a minimum and ensure that all cables are fireproof-covered and that trenches within the building are isolated one from another.

Mr. Bayley discussed the precautions he is taking in connection with the water system of protection for use in the event of an air raid. Under such conditions I should prefer to leave the equipment on automatic protection, and, should the nature of the load or size of the plant justify further precautionary steps, I should advise a pressure storage tank to guard against drop in pressure of the town's main, which would be heavily drawn upon by the various Corporation and private A.R.P. organizations.

I should like to ask the authors' opinion of the effect of CO_2 or methyl bromide on various metals. Would these fire-fighting media be dangerous in a paint factory?

Mention of the cost of automatic fire-fighting equipment has been made in the discussion; the cost of the Mulsifyre system for protecting two outdoor 12 500-kVA 11/33-kV power transformers is approximately 3 % of the total cost of plant and foundations, in those cases where the direct pressure of the town's main is adequate.

Mr. R. E. Eberhardie: It is sometimes stated that if an inert gas is used for fire-fighting it is necessary that the building should be gastight. This statement is misleading. In actual practice the officer responsible for submitting the CO_2 protection scheme would take note of the windows, doors and other apertures in the building, and, where necessary, provide for louvres and automatic methods of closing the necessary doors. This would not interfere with the ventilation during normal operation.

With regard to the provision of water sprinklers, which it has been suggested is the ideal method of protecting electrical plant; as was shown during the demonstration, a 3-in. pipe is insufficient to maintain an adequate supply

of water for the sprinkler system as well as the "back-up." When considering water protection an engineer must therefore take cognizance of the certainty of maintenance of pressure, the certainty of continuity of supply, and the probable effect of severe weather.

Mr. Nuttall referred to the question of the danger of explosion due to CO_2, and the possibility of flame acting upon the CO_2 to form fresh lethal gases; CO_2 is an extremely stable chemical compound, and we have no evidence that any chemical decomposition takes place under the conditions in which it is applied to fire-fighting. Moreover, the gas is discharged at freezing temperature, and will therefore tend to cool rapidly the molecules of vapours and solids it comes into contact with.

There is considerable misapprehension regarding explosions which have occurred in switches. These can be attributed to the expansion of oil gases given off by the oil within the switch itself.

There is also a considerable amount of misunderstanding with regard to the toxic effects of CO_2. The toxicity of a substance is its propensity for causing changes in the blood-count, and the blood structure. CO_2 causes no change in the blood-count, and is non-toxic. The only danger to be apprehended from CO_2 is due to the fact that it excludes oxygen. If a person has been overcome by CO_2 all that is necessary is to place him in the open air as soon as possible. So far from being toxic, CO_2 is a respiratory stimulant, and it is common hospital practice to administer CO_2 with oxygen.

I have heard it suggested that the automatic application of a protective system should be delayed until an audible alarm has been sounded. This suggestion is likely to prove dangerous. In a recent switch fire an explosion occurred inside a switch, causing a spread of oil. The CO_2 system instantly functioned and extinguished the fire, but there was ample evidence that the initial flame was fairly widespread, and had the application of the extinguishing medium been delayed there would have most probably been a very serious fire.

Mr. G. Eyre: Regarding the E.R.A. tests utilizing water as the fire-fighting medium I regret that no mention is made in the paper of emulsification in relation to oil fires, although if the recommended minimum pressure of 50 lb. per sq. in. at the highest nozzle were employed emulsification would be the natural result with efficiently designed nozzles.

It is interesting to note that whilst atomized water may deal with certain fires it is an essential feature of the fire protection system that it should emulsify the oil, to be sure of dealing with fires of the fiercest type.

The temporary emulsion formed by the discharge of powerful broken streams of water is of the "oil in water" type, and is formed by the impact of the high-velocity water breaking up the oil into tiny globules and enveloping each oil globule in a seal of water. Under this condition the gases cannot escape from the oil to the atmosphere to burn, and "flash-back" or re-ignition cannot occur.

Mr. J. Kennedy: I was interested in Mr. Bayley's remarks in regard to the layout and construction of new substations. In planning new construction there is every opportunity to reduce and to localize fire risks, and advantage should be taken of this fact.

I cannot accept Mr. Bayley's conclusion that water is the best fire-fighting medium for indoor risks. The tests described in the paper prove that under automatic conditions methyl bromide and CO_2 can be used satisfactorily not only on indoor risks but on outdoor ones also. Mr. Bayley revealed his own misgivings that damage to installed gear, from accidental cause or even from a nearby bomb explosion, might occur through accidental discharge of the water-type protective gear. Installation of either of the gas systems would have avoided this risk, since they are incapable of damaging electrical gear.

I am completely in agreement with Mr. Nuttall and other speakers that automatic operation of fire protection gear is essential if fire is to be extinguished before it can cause much damage, and I believe that to-day most electrical engineers take this view. I feel, too, that the extinguishing gear ought to be entirely independent and that if water-type gear is used the necessary pressure tanks and pumps should be installed to obviate the risk of water-main failure.

The ideal dwarf wall should be several feet higher than the transformer, and should cover it on three sides. The E.R.A. film showed that the fires obtained in the tests on the gas systems were much less extensive than those which occurred in the tests with other systems, and this, in my opinion, was due in no small degree to the screening erected in connection with these tests.

I would inform Mr. Nuttall that the density of methyl bromide vapour is $3\frac{1}{4}$ times that of air, and nitrogen is added to raise the total cylinder pressure to 50 lb. per sq. in. Methyl bromide vapour has an actual pressure of some 26 lb. per sq. in. As to portable methyl-bromide apparatus for cable tunnels, and the question of risk to the operators, I can only say that we supply portable units containing 72 lb. (net) of methyl bromide—we only used 120 lb. to extinguish the outdoor transformer fire—and that these units are used without mask or breathing apparatus, without harm to the users. The cable-gallery fire shown in the E.R.A. film was actually extinguished with a methyl-bromide portable unit. Nevertheless, every precaution should be taken in dealing with underground fires, from the point of view of possible toxic fumes both from the methyl bromide and from burning rubber and equipment. It is therefore very difficult to indicate any safe limit for time of exposure. We have records for exposure to raw methyl bromide extending to $1\frac{1}{2}$ hours in a concentration initially of the order of 74 %, this concentration being gradually reduced by the ventilation natural to the engine room in which the discharge took place. Nevertheless, I would not recommend prolonged exposure, and for practical purposes would prefer to set a limit of 3–4 minutes. Fires extinguished by methyl bromide do not normally produce fumes having any appreciable effect on metals, nor do paint or cellulose fires so extinguished generate noticeably toxic fumes.

Mr. Eberhardie stated that CO_2 is not toxic—that it can only cause death by suffocation and that small quantities of CO_2 can be used for resuscitation purposes. This is, of course, true; but it is equally true that strychnine in small doses is a tonic, while large doses are not infrequently fatal.

Messrs. J. Hacking and **R. A. McMahon** (*in reply*):

General

A number of speakers at this Centre have raised questions of a similar nature to those raised in one or other of the other Centres, and in as far as such questions have already been dealt with in the main reply no further reply will be made here. In the same way the questions of interest that have been raised by Mr. Nuttall have been answered by Mr. Eberhardie and Mr. Kennedy.

Water

Mr. Bayley raises the question of possible operation of controls of automatic water installations by mechanical shocks due to bombs, and the consequent risk of affecting supplies if the apparatus protected is not of the outdoor type. This risk is certainly present. It can be dealt with in the way proposed by Mr. Bayley, and in an attended station there would not appear to be much risk in relying on subsidiary hand valves. On the other hand, we do know of cases in which subsidiary hand valves have been incorrectly operated, with unfortunate results. In view of the advantages of rapid action, we should prefer to see fully automatic operation with cut-outs only on gas systems where necessary to protect maintenance staff. Mr. Bayley's difficulty is primarily because he is envisaging the application of water to gear which will suffer damage by water. There would appear in this case to be a strong argument in favour of an alternative form of protection.

Walls

Mr. Broughall refers to the question of design of walls. We agree that it is not possible to design dwarf walls which will prevent jets of oil under pressure being ejected over the wall. They can only deal with oil which falls in the immediate neighbourhood of the transformer. The possibility of oil jets can only be dealt with by having very high walls, and it is necessary to consider each case on its merits. For instance, if a transformer were in the middle of a field with nothing near, walls would be unnecessary and one would even be inclined to omit any fixed fire-fighting installation, as in any case the chances are that a complete rewind would be necessary. On the other hand, even a small transformer placed close to other important gear would require a scheme which would prevent burning oil from it reaching other gear and causing further fires.

THE LIMITATION OF TRANSFORMER NOISE

By B. G. CHURCHER, M.Sc., Member,* and A. J. KING, B.Sc.Tech., Associate Member.*

(*Paper first received* 6*th September*, 1939, *and in revised form* 25*th June*, 1940; *read before* THE INSTITUTION 28*th March, and before the* NORTH-EASTERN CENTRE 8*th April*, 1940.)

SUMMARY

The paper describes a quantitative investigation into the subject of the noise emitted by transformers, and possible measures for its limitation. Permissible noise-levels for different situations are discussed and data for residential districts given. The generation of transformer noise is considered. Methods for limiting noise, applicable to a transformer as a unit, are discussed, and results obtained with one based on the interception of vibration transmitted from core to tank are given. Methods applicable externally to a transformer are also discussed. The electromagnetic, thermal and economic considerations which arise in the employment of the various methods are discussed and examples are given.

CONTENTS

(1) Introduction.

(2) Conditions giving Cause for Complaint.

(3) The Generation of Noise in Transformers.

(4) Methods of Noise Limitation Applicable to a Transformer as a Unit.
- (*a*) General.
- (*b*) Choice of core material.
- (*c*) Core construction.
- (*d*) Effect of flux density.
- (*e*) Interception of vibration transmitted from core to tank.
- (*f*) Tank construction.

(5) Noise Limitation by External Means.
- (*a*) General.
- (*b*) Effect of distance.
- (*c*) Effect of enclosure.
- (*d*) Use of barriers.
- (*e*) Penetration of noise into buildings.

(6) Conclusions.

(7) Acknowledgments.

(1) INTRODUCTION

The standardization of alternating-current power distribution in Great Britain has brought into prominence the question of the noise emitted by transformers. Not only is the use of transformers now more widespread than formerly, but the size of unit required in distribution has increased. Further, for the sake of economy in distribution, transformers are placed as nearly as is practicable to the centre of gravity of the load. The need for supplying a domestic load frequently leads to the installation of transformers in districts or locations where quietness may reasonably be demanded, especially during night hours. It is clearly desirable that complaints of excessive noise from transformers, possibly followed by legal proceedings, should be anticipated and adequate steps taken to avoid them rather than that the need for abating the noise of transformers already installed should arise. In many cases within the authors' experience, the need for noise-abatement measures with existing installations has arisen owing to its not having been realized that the conditions were such that complaint was probable. Hence it is important that the noise aspect of a transformer installation should be considered in the planning stage and not be dealt with as an afterthought. It is then often possible to embody the necessary measures without undue difficulty. It is generally appreciated that an engineering problem requires a solution which is not only technically practicable but which is also economically satisfactory. With so complex a subject as noise limitation, an analytical approach is advisable if unsuccessful or uneconomic results are to be avoided. Not only should the principal factors entering into the problem be fully appreciated but their quantitative effect on the final result should be capable of prediction within reasonable limits. It does not follow that because a certain measure or device is effective under one set of conditions it will be effective, or even relevant, under another set of conditions. Although the present paper deals specifically with transformer noise, many of the questions discussed are relevant to noise from engineering plant and apparatus in general.

Three principal elements are present in noise-limitation problems, namely the source of noise, the hearer, and the sound attenuation between source and hearer. The acoustic output of a transformer (the word "transformer" includes oil, tank and other fittings) is dependent on a number of electromagnetic and mechanical factors which are intimately bound up with, and generally dictated by, the design of the apparatus as an efficient transformer of electrical energy. It is seldom possible to vary electromagnetic or mechanical features from the point of view of noise limitation without meeting important restrictions related to efficiency and cost and, in some circumstances, thermal dissipation. The attenuation between source and hearer depends, in the case of purely air-borne noise, on the acoustical properties of the building (if any) in which the hearer is located, on distance, on any obstructions present in the sound field, and on the degree of enclosure of the source. Besides acoustical considerations, the latter may raise important questions of thermal dissipation, and various points of installation practice and cost. Hence the problem of noise limitation in relation to engineering plant is many-sided and cannot usefully be envisaged simply as a matter of acoustics.

* Metropolitan-Vickers Electrical Company, Ltd.

It is only by viewing the problem in all its aspects that the various alternative solutions can be envisaged and appraised and hence the most suitable chosen.

Discussion of the relative merits of schemes for the limitation or abatement of transformer or other noise is not infrequently obscured by vagueness as to the amount of abatement visualized or claimed. Small reductions in noise, e.g. 5 or 10 phons, are sometimes useful in borderline cases; but in other cases, to secure freedom from complaint with a margin, reductions of 20 phons or more are required. It is with the latter order of abatement that the present paper is mainly concerned.

(2) CONDITIONS GIVING CAUSE FOR COMPLAINT

It is generally accepted that the loudness of a noise is the best measure of its undesirability which is at present available. The conception of degrees of "nuisance" or "annoyance" and the possibility of their quantitative assessment has sometimes been suggested. Some investigators of this interesting and somewhat intangible question have considered that their experiments demonstrate a distinction between loudness and "nuisance." Other investigators have not felt able to draw such a distinction. The opinion is sometimes expressed that high-pitched sounds are more distracting than low-pitched sounds of the same order of loudness, and it may be that a distinction between loudness and "nuisance" exists only for noises containing important high-frequency components. With transformer noise the loudest component rarely exceeds 400 c./s., and components of higher frequency than 800 c./s. are usually unimportant. Although the general question of the relation between loudness and "nuisance" must remain open until it has been thoroughly explored, experience shows that loudness forms an adequate basis for the solution of practical noise problems. For this reason the British Standards Institution adopted in 1936 a unit of equivalent loudness, the phon,* which has since been adopted internationally. Briefly, the phon enables steady noises of all types to be expressed in terms of a common standard or reference tone of 1 000 c./s. The E.L.† of a noise is numerically equal to the intensity level of the reference tone which to a representative group of observers sounds as loud as the noise, certain stipulated conditions being observed. The phon constitutes the primary standard to which the performance of the portable noise-meters required for ordinary purposes is referred. The experimental realization of the phon‡ requires the rigorous methods and adequate resources appropriate to a fundamental standard, and is not a matter which the user of noise-meters need ordinarily consider in detail. It is important, however, that he should satisfy himself that broad claims that particular meters are capable of measuring noise in general in phons are supported by specific evidence, which covers the types of noise he desires to measure. Some investigators have used what are termed "sound level meters" to the indications of which the term "phon" is applicable only when the noise consists substantially of a single tone. With transformer noise these instruments may read as much as 15 phons low, which may explain the low values sometimes quoted for quite normal transformers.

It is now recognized that the question of whether a sound is to be regarded as a noise or not is decided on subjective and not on physical grounds. Hence noise is defined as "sound which is undesired by the recipient."* Many instances occur in which a given sound may be said to be pleasing to a listener and, without contradiction, an objectionable noise to an involuntary hearer. It may safely be assumed that, except for technical purposes, the sound of a transformer is always undesired. In general, objection to noise of any kind arises because the loudness is sufficient to cause interference with the hearing of desired sounds or simply because it gives rise to distraction or discomfort. A discussion of the psychological aspects of noise would be out of place in the present paper, and the influence of the foregoing considerations can be briefly illustrated by examples.

Take first the rather extreme case of a large engineering shop devoted to heavy machining, fitting, and erecting operations. During working hours the general noise-level may seldom fall below 85 phons. Hammering on sheet metal, or other specially noisy operations, may cause peaks of 100 phons or more. The most obvious objection to such noise is interference with conversation. Under normal conditions conversation is carried out at a level of about 60 phons. If one sound is 20 phons louder than another, the former may entirely mask the latter, leading, in the present example, to shouting if speech is to be heard even a short distance away. Interference with telephone conversation can, of course, be eliminated by suitable measures. A level of 85 phons is certainly disagreeable and inimical to connected thought, but evidence that its distracting influence imposes a serious strain with ordinary manufacturing operations is scanty. A transformer of not more than, say, 2 000 kVA operating under such conditions would be incapable of causing a nuisance, as it would be quite inaudible, except at very close quarters.

In a general office, the usual causes of noise, such as the shuffling of papers, telephoning, conversation, typewriting, walking about, sometimes result in a noise level that makes connected thinking difficult. While the level may not always be sufficient to interfere with telephone or ordinary conversation, speech in noisy surroundings has a cumulative effect, since each person tends to raise his voice in order to be heard. Hence, apart from the exclusion of external noise, steps are often taken to limit the internal level in offices by the removal of noisy office machinery, by providing a large amount of acoustical absorption, or by other means. Without attempting to lay down a standard, a level of 60 phons appears to be as great as is advisable for an ordinary office. In certain cases a lower figure would be advisable, e.g. in rooms accommodating persons engaged on work requiring considerable mental concentration. Transformers may be installed in the basements of offices, public libraries, or schools. The possibility of the room noise-level due to a transformer reaching a value of, say, 50 phons then requires attention.

* "British Standard Glossary of Acoustical Terms and Definitions" (B.S. No. 661—1936).

† Throughout the paper the abbreviation E.L. is used for "equivalent loudness."

‡ This is discussed in a previous paper. See B. G. Churcher and A. J. King: *Journal I.E.E.*, 1937, **81**, p. 57.

* B.S. No. 661—1936.

The most exacting conditions arise with places intended for relaxation rather than work. Quiet may be legitimately demanded in flats, dwelling houses and the grounds attached to them, the sleeping quarters of hotels, and in hospitals. The occupant is normally in a receptive condition, i.e. unprotected by the partial or complete insensibility to noise which concentration on a task tends to give. A tolerable noise-level is far below that which would cause interference with conversation or the hearing of broadcast speech or music. It is a question of a comfortable level, i.e. one that does not disturb rather than one permitting sufficient intelligibility. The obtrusiveness of a given source of noise depends considerably upon whether any other noise is present, i.e. upon what is usually termed the background noise-level. It is only under special circumstances that complete silence, or zero background-level, can be experienced. Thus in a soundproof chamber of a laboratory, a noise of 10 phons is plainly audible to persons of normal hearing, and indeed can be measured by aural comparison. But such feeble sounds can rarely be heard under ordinary circumstances because they would be masked by the background level, which is rarely less than 10 phons and usually more. The completeness with which one sound masks another depends upon the relative frequencies of the sounds, i.e. upon their pitch or, in the case of complex sounds, on their relative compositions. But it may be assumed that, apart from extreme cases, where the sounds differ radically in composition, a noise of a given level will be almost completely masked by one of 20 phons higher level. Even a preponderance of 10 phons will greatly diminish the obtrusiveness of the quieter noise. So it is evident that the disturbing effect of the noise of a given transformer will be greatly dependent on the background level in the location in question. Some values observed on domestic premises in residential districts are given in Table 1. They are based on four cases. The levels were found to vary considerably during a given period, on different days and on different premises, so that only the range of approximately sustained levels can be given, together with the maximum momentary values.

Thus very low background levels are sometimes reached. Experience in a number of cases of transformer noise in quiet residential districts indicates that complaint is liable to arise if the level immediately outside a house much exceeds 40 phons. This will generally correspond to about 30 to 35 phons within a room in the house, the windows being open, and it is seen from Table 1 (No. 2) that this order of level may be no more than that already present in the room.

In considering these figures, we must not overlook the curious psychological factors which may sometimes be met with in cases of complaint. A person's estimation of or attitude to a noise is influenced by what he is accustomed to and is also liable to depend considerably on whether he himself or someone else is responsible for the noise. Again, in investigating a complaint that sleep at night is impossible owing to the hum of a neighbouring transformer, it may be necessary to remove a loudly ticking clock before the transformer noise reaching the bedroom can be heard or measured.

The E.L. (equivalent loudness) values of transformer noise to be given were measured by two types of meter, namely a 2-telephone subjective meter described in a previous paper,* employing in most cases a group of 10 observers, and an objective meter of a new type not yet described. Where both methods were used satisfactory agreement was obtained. Most of the measurements were made in a highly lagged room, giving free-space conditions and zero background noise-level. The E.L. of the noise of a transformer is stated as the mean of readings at several positions round the transformer, the distance being 1 m. from the nearest point. It is usually found that at no position does the E.L. differ from the mean by more than 2 or 3 phons. The measurements are made at a height approximately equal to half the height of the transformer. The variation of E.L. with height is normally very small.

Table 1

No.	Location	Time	Windows	Sustained range	Occasional momentary value
				phons	phons
1	Living room	Day		10–40	75
2	Bedroom	Night	Open	20–35	55
3	Bedroom	Night	Closed	5–20	40
4	Garden	Day		25–60	70
5	Garden	Night		10–45	70

(3) THE GENERATION OF NOISE IN TRANSFORMERS

Transformer noise arises from audio-frequency vibrations of the core and coils, which, in the case of "dry type" units, radiate sound waves of corresponding frequency and amplitude. With oil-immersed transformers, the vibrations are transmitted through the oil and tank walls before being radiated as sound. The vibrations originate mainly in the core. Under load, the passage of current through the windings sets them in vibration. If the load-current wave-form is substantially sinusoidal, these vibrations will be of double the frequency of the current, namely 100 c./s. in the case of a 50-cycle transformer. However, experience does not suggest that the noise of power transformers varies appreciably with load. A test was carried out on a 60-kVA distribution transformer with the secondary winding short-circuited. With full load current passing through the windings and zero background noise, the transformer was inaudible. By means of data available from a research on the forces acting on transformer windings under short-circuit conditions, the approximate amplitude of dilatation of the outer coils of a 2 000-kVA core-type transformer was estimated for full-load current. It was found that the amplitude was such as to produce an intensity level which at 100 c./s. approximates to threshold intensity. Even if a large transformer under full-load current short-circuit conditions produced an audible sound, such sound would be completely masked when the core was excited. It is possible for a heavy-current lead in close proximity to the tank side to set up audible vibration, but too-small spacing has usually to be avoided for heating reasons. Hence, in general, only core vibration need be considered.

Core vibration arises principally from the magnetostric-

* B. G. Churcher and A. J. King: *Journal I.E.E.*, 1937, 81, p. 57.

tion effect in the core material.* The magnetizing of a strip of sheet steel causes a minute increase in length or extension, with a corresponding reduction in cross-section. The extension partly or wholly disappears when the magnetizing field is removed, and is independent of the direction of magnetization. Hence in a transformer core there is a minute deformation at each half-cycle of magnetization, so that in a 50-cycle transformer the core surfaces pulsate at a fundamental frequency of 100 c./s.

Fig. 1 illustrates the order of magnitude of the magnetostriction effect in 4 % silicon steel. It will be seen that during a cycle of magnetization the extension per unit length ($\delta l/l$) is not proportional to B and that a pronounced hysteresis effect or time-lag exists between B and $\delta l/l$. Hence, even though the wave form of the applied voltage and therefore the core flux be sinusoidal, the variation of extension during a cycle is far from sinusoidal, i.e. in addition to the fundamental frequency of 100 c./s. there are pronounced harmonics, both odd and even multiples of 100. The noise emitted is therefore complex in character, as will be shown. It will also be seen that the extension per unit length is exceedingly small, being of the order of 10^{-6} in. per inch length of core for a maximum flux density (B) of 10 000. However, the length of the core of a transformer of a few hundred kVA is sufficient to cause an undesirably loud noise owing to the very small amplitude required to produce appreciable sound. The latter point may be illustrated by a simple example. Suppose a surface of area 100 sq. in. vibrates sinusoidally and uniformly with an amplitude of 0·0001 in. at 300 c./s.: then at 1 m. distance the E.L. will be approximately 70 phons.

The sound spectrum from the simplest possible form of core, a single ring punching magnetized by a conductor located at the centre, is given in Table 2. It is seen that components of appreciable magnitude exist up to 1 100 c./s. at a maximum flux-density of 10 500 lines per cm^2 extending to 1 400 c./sec. at $B_{max} = 14\,800$. Each component contributes to the noise experienced by a hearer, but not, of course, in direct proportion to the E.L. values. The largest component is seen to occur at 300 c./s. at the lower and 500 c./s. at the higher density. In a normal transformer the sound spectrum is modified by several factors, such as the use of unequal densities in leg and yoke of the core, the presence of joints, the constraint imposed by the particular type of core construction used, and the elastic properties of the tank, especially if in the latter natural modes of vibration are present the frequencies of which are close to 100 c./s. or multiples of it.

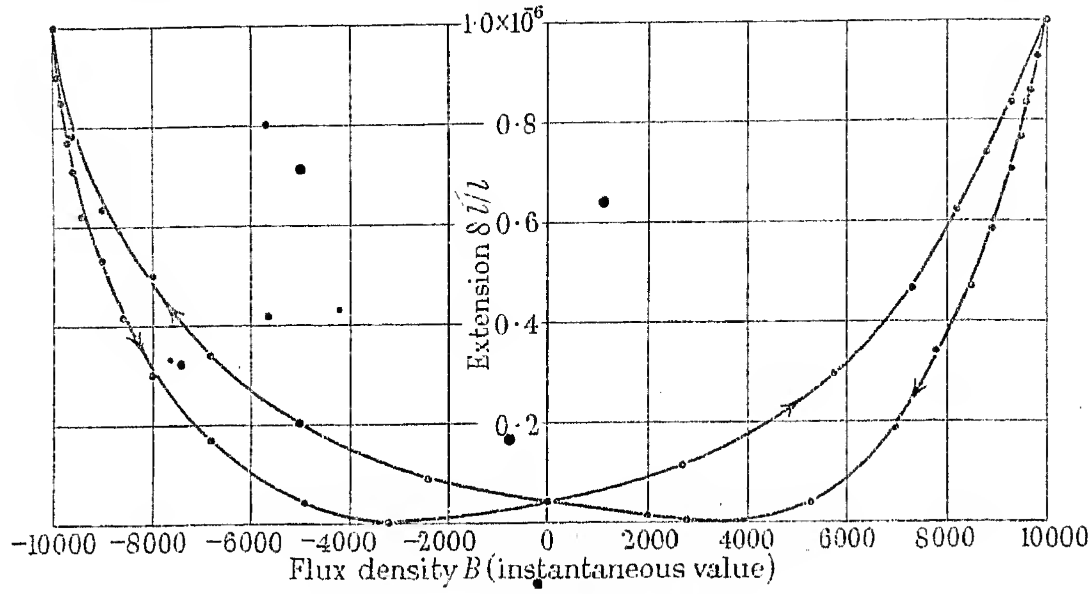


Fig. 1.—Relation between flux density and extension, for 4 % silicon steel.

Comparative tests on ring cores in air with and without interleaved joints and rectangular cores with joints show a considerably greater noise-level for the latter for similar conditions of cross-section, grade of steel, and flux density.

Table 2

SOUND ANALYSIS OF NOISE FROM SINGLE RING PUNCHING OF 4 % SI STEEL MAGNETIZED BY CENTRAL CURRENT. FREQUENCY OF APPLIED VOLTAGE, 50 C./SEC.

Frequency of component (c./sec.)	Equivalent loudness of component at distance 1 m. (phons)	
	$B_{max} = 10\,500$	$B_{max} = 14\,800$
100	0·5	9·5
200	6·0	16·0
300	36·5	50·5
400	28·0	40·5
500	26·5	52·5
600	14·5	32·0
700	19·5	33·0
800	18·5	32·0
900	16·5	22·0
1 000	13·0	19·5
1 100	18·0	25·5
1 200	—	24·0
1 300	—	18·5
1 400	—	21·5

* This view was confirmed in 1934 by the authors' noise measurements and analyses on ring cores and magnetostriction measurements on strip specimens. In 1936 Dr. Swaffield, at University College, London, showed, in a confidential report, by means of noise analysis and direct magnetostriction measurements, that the noise from a long ring core could be wholly accounted for by magnetostriction. According to Swaffield and Alexander (*Beama Journal*, October, 1937), magnetostriction hysteresis was fully established by 1931. Fig. 1, which is inserted as being of general interest, was obtained on a strip specimen after Dr. Swaffield had obtained a similar loop on a ring core. The authors' work on the effect of clamping and joints in ring and normal transformer cores, the effect of form factor and other matters dealt with under (3), was carried out between 1930 and 1935.

This appears to be due to the smaller rigidity of the rectangular jointed core and to forces on the laminations at the joints where the flux crosses from one lamination to another, in addition to the magnetostrictive forces.

A matter which may be noted here is the influence of supply wave-form on noise. We have seen that even with a sinusoidal flux wave-form the wave form of the magnetostrictive extension, and hence the sound pressure wave, contains harmonics. In general, a distortion of the flux wave, due to the application of a distorted voltage-wave to a transformer, is to be expected to lead to a further generation of harmonics in the sound wave and an increase in E.L. A test was carried out on a ring core of 4 % Si steel in which the applied-voltage wave form was varied by inserting resistance in the circuit. It was found that when the form factor was increased from 1·11 (sine wave) to 1·18 the E.L. increased from 36 to 48 phons. It does not follow that these figures would be applicable to normal transformers, but it illustrates the importance of known wave-form conditions in measuring transformer noise if the E.L. values are to be on a definite basis. Tests on other grades of steel showed an increase of noise with form factor.

The effect of a departure from normal frequency on the E.L. of a transformer will be very dependent on whether any of the natural modes of vibration of the core and tank as a whole approach 100 c./s. or multiples of it. If such is the case, the E.L. may increase or decrease with frequency. Fortunately, in practice there is generally no difficulty in ensuring that the frequency is very close to the nominal value.

(4) METHODS OF NOISE LIMITATION APPLICABLE TO A TRANSFORMER AS A UNIT

(a) General

We may conveniently consider noise-limitation methods under two general headings: first, those in which the noise is limited by the design of the transformer or by the incorporation of noise-suppressing devices forming part of the transformer as a unit; and secondly, those in which the noise is limited by devices external to and separate from the transformer. As previously stated, we are primarily concerned with methods capable of effecting a reduction in noise level of 20 phons or more, i.e. those which would effect a radical improvement in case of actual or potential complaint. It may be helpful to note that the ratio of the loudness, as experienced by a normal observer, as between 70 phons and 50 phons is approximately 4·8 to 1. To effect a reduction of 20 phons requires a reduction of the acoustic energy to approximately one-hundredth, and of the acoustic pressure to one-tenth, of its original value.

(b) Choice of Core Material

A direct and fundamental method of limiting transformer noise would be to choose core material having a low magnetostrictive effect. Three grades of silicon steel in general use show the magnetostriction values given in Table 3. The specimens were cut along the rolling direction of the sheet.

To estimate the relative noise-levels for the different steels would require a somewhat lengthy calculation, postulating a simple type of core, such as a ring core, and from the shape of the magnetostriction curve deducing the relative amplitudes of the harmonics produced when the core is excited at a given flux density and frequency. However, since the radiated acoustic pressure is proportional to amplitude for a given frequency and since we are looking for differences of 10 to 1 or more, the differences are too small to promise any appreciable advantage. Some noise tests on these three materials, using ring cores where magnetostriction would be the only cause of noise, gave the results shown in Table 4.

Table 3

MAGNETOSTRICTION EFFECT WITH DIFFERENT GRADES OF STEEL SHEETS

Grade of steel (% Si)	$\delta l/l \times 10^6$	
	$B_{max} = 10\,000$	$B_{max} = 13\,000$
0·2	0·9	1·4
1·5	0·75	2·5
4·0 (transformer steel)	1·3	2·8

As the cores are of similar dimensions and mechanical properties the results confirm the conclusion drawn from the magnetostriction values, that within the range of normally-used sheet steels the noise level is not appreciably affected by the grade of steel.

It has been found* that steel containing larger percentages of silicon has a smaller magnetostriction effect, the magnetostriction having a very low value for 6 % to 6½ % Si. Noise measurements on ring cores of 4 % and 6 % Si steel of identical dimensions, carried out by the authors over a range of flux densities, gave rather higher noise-levels for the 6 % than for the 4 % steel. However, the comparison may not be conclusive, owing to the critical dependence of magnetostriction on silicon content between 6% and 6·5%. Analysis showed the actual silicon content to be 6·1 %. The extreme brittleness of such material is a serious obstacle to its practical employment. Also, while some advantage in respect of reduced core-loss is to be expected from the increased percentage of silicon, the extra cost would only be justified if associated with a substantial reduction of noise.

Table 4

EFFECT OF GRADE OF STEEL ON NOISE LEVEL. (RING CORES 15 IN. OUTSIDE DIAM., 9 IN. INSIDE DIAM., 2 IN. AXIAL LENGTH, $B_{MAX} = 10\,400$, FREQUENCY = 50 C./SEC.)

Grade of steel (% Si)	Phons at distance 1 m.
0·2	39
1·5	36
4·0	36

* British Patent No. 480235—1938.

It has long been known that Permalloy (21·5 % Fe, 78·5 % Ni) has, for a certain steady flux density, sensibly zero magnetostriction. However, its cost and the fact that it is saturated at a density of the order of $B = 11\ 000$ clearly preclude its use for power-transformer construction.

Thus at present a solution of the noise problem by choice of core material seems hardly practicable, but with the development of new materials the position may be altered.

(c) Core Construction

Most power transformers now constructed by the firm with which the authors are associated are of the " core type " with interleaved joints, so that except where otherwise stated this type is assumed in the present discussion.

Experience in the construction of large numbers of cores has brought out the importance, from the point of view of noise, of careful interleaving and of adequately distributed clamping pressure, provided by sufficiently extensive and stiff end-plates, so that no appreciable length of core is left unclamped. It has not been found that the use of exceptionally large pressures leads to an appreciable reduction in noise. This is to be expected since, in so far as the noise is due to magnetostriction, the legs or yoke of the core will extend as a whole with each alternation of flux, so that lateral pressure will not appreciably affect the extension. This was confirmed by a test (see Table 5) on a 100-kVA core in air.

Table 5

Effect of Tightening Core Bolts on Noise (100 kVA, 3-phase core, $B_{MAX} = 10\ 400$, frequency = 50 c./s.).

Clamping condition	Phons
Core bolts " thumb tight "	51
Core well clamped by 3 turns of nuts ..	52
Core very tightly clamped (3 additional turns)	50

Some experiments were then carried out to ascertain whether a much more complete consolidation of a core, such as might be obtained by cementing the punchings together over their whole surface by some strongly adhesive material, would have appreciable effect. A baking coil varnish was used. A coat of varnish was applied to both sides of each lamination and allowed to dry sufficiently to produce a " tacky " surface. The core was then assembled and baked under a lateral pressure of the order of 1 lb. per sq. in. at a temperature of 110° C. for about 17 hours. As a matter of interest, a ring core was included. The noise measurements were made in air, i.e. without tank or oil, and the results are given in Table 6.

Noise observations on the uncemented ring core, and also on a single ring punching, showed that the major part of the sound was radiated from the ends of the cylinder rather than from the outer surface. The axial vibration took place in waves distributed round the circumference. The cemented core was exceedingly rigid and " dead " when struck axially, but when struck radially emitted a note corresponding to 1 200 c./s., which was quickly damped out. The considerable reduction of 33 phons is probably mostly due to the greatly increased rigidity and damping of the core in relation to axial distortion. It was thought of interest to ascertain whether in a normal core with interleaved joints the film of oil which is normally present between the punchings exerts any damping effect, especially in regard to the repulsive forces between laminations at the joints where flux crosses from one lamination to another. Noise measurements were therefore made on the 10-kVA single-phase core, which was of normal construction, before and after it had been soaked in transformer oil for a period, the measurements being made with the core in air. It is seen that the effect of oil immersion is to reduce the noise level from 48 to 37 phons. Cementing reduces it to 26 phons. It is, of course, only the second reduction which is of significance for practical purposes and it must not be overlooked that when the oil and tank are added, the absolute, if not the relative, noise levels may be modified. However, it is evident that only under very exceptional circumstances would a level of the order of 37 phons require reducing, so that it becomes of interest to ascertain whether cementing gives useful reductions for larger cores. From Table 6 it is seen that within the limits of measurement no appreciable reduction is obtained with a 60-kVA 3-phase core. Mason* arrived at similar conclusions with regard to the clamping and cementing of cores.

Table 6

Effect of Cementing Cores (4 % Silicon Steel, $B_{MAX} = 13\ 000$, frequency = 50 c./s.).

Core	Condition	Noise level (phons)
Ring core, 15 in. outside dia., 9 in. inside dia., 1 in. axial length	Tightly bound with tape	43
	Cemented	< 10
10-kVA single-phase core	Before oil immersion	48
	After oil immersion	37
	Cemented	26
60-kVA 3-phase core	After oil immersion	65
	Cemented	64

As regards forms of core other than the " core type," it is understood that the circular shell type, such as may be used for small transformers, is claimed to offer an advantage in respect of noise, but the authors have seen no quantitative information on the point.

(d) Effect of Flux Density

A measure sometimes proposed is to design the transformer for a working flux-density lower than would normally be used if noise were of no consequence. Whether this technically simple solution is economically practicable depends on circumstances, particularly the size of the unit involved and the level to which it is desired to reduce the noise.

* *B.T.H. Activities*, July–August, 1938.

Fig. 2 consists of a family of curves giving approximate noise-levels for transformers of different ratings and at different flux-densities. The noise levels are in no way definitive and apply only to particular conditions. However, they are sufficient for comparative purposes. Let us assume that installation conditions, distance and other factors are such that it is not permissible to exceed a level of 50 phons at a point a few feet from the transformer; also that $B_{max} = 13\,000$ is the normal working flux density for standard transformers. It will be seen that if we are dealing with a small transformer, e.g. 50 kVA, the level at normal flux density is not much in excess of that desired. Thus, if we take an actual transformer under the conditions to which the curves relate and reduce the flux density to $B_{max} = 12\,400$, the level will be reduced to 50 phons; but the rating will be diminished in the process. To regain loss of rating due to reduced flux density, especially if such reduction is sub-

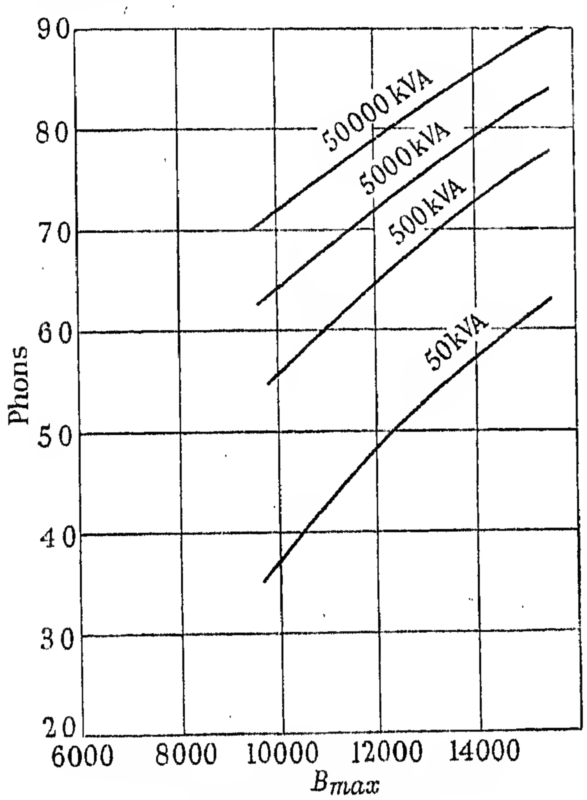


Fig. 2.—Relation between equivalent loudness and flux density, for 3-phase transformers.

stantial, might need a complete reconsideration of the design of the transformer, since with unusually low core densities it might be necessary to modify radically the relative proportions of iron and copper. However, by considering the effect of a small change in density and adopting simplifying assumptions, we can roughly assess the effect of a reduction in density. Suppose the density is reduced by 10 % and we decide to keep the core section, winding depth, and conductor size, unaltered. To regain the lost voltage, the turns—and hence the winding length—would need increasing by 10 %, with a corresponding increase in leg length. The copper loss would be increased 10 %, but if iron and copper losses were of the same order, this would be largely offset by decreased iron loss, also amounting to rather more than 10 %. Further, an increase in dimensions of the transformer would in itself give rise to a small increase in noise level, to overtake which a small further decrease in flux density would be needed. Other factors which might or might not be important, such as reactance, would be affected by change in dimensions, but it is evident that a reduction of 10% in flux density would involve an increase in active material of about the same order, with a corresponding increase in tank size and oil quantity. It would then have to be considered whether the increased cost of the transformer was justified by the comparatively small reduction in noise level or whether the desired result could not be obtained by cheaper means.

If we refer to the curve in Fig. 2 for a 500-kVA trans-

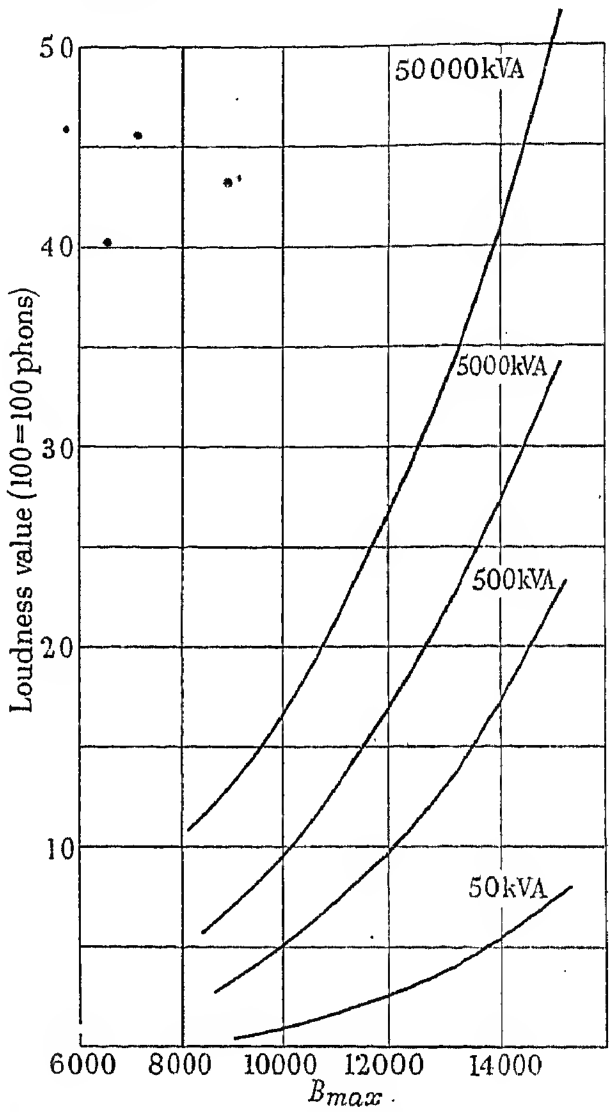


Fig. 2A.—Relation between loudness and flux density, for 3-phase transformers.

former, it is clear that to bring the noise level down to 50 phons would mean a reduction in flux density (B_{max}) from 13 000 to something less than 9 000, involving a substantial increase in dimensions. With large transformers the required density would clearly be prohibitively low. We must therefore conclude that it is technically possible to effect a substantial reduction in noise level by reducing flux density, but, especially for large transformers, such a method is quite impracticable economically.

In Fig. 2A, the data of Fig. 2 are shown in terms of loudness* rather than E.L., i.e. the ordinates are proportional to the loudness sensation experienced by a normal hearer. As is to be expected, the curves of Fig. 2A are much more in accord with aural impressions, e.g. that the loudness of a transformer increases fairly rapidly with flux density and that a substantial increase in loudness is associated with a tenfold increase in kVA. It may be

* B. G. Churcher: *Journal of the Acoustical Society of America*, 1935, 6, p. 216.

noted that in terms of this loudness scale (chosen arbitrarily so that 100 units = 100 phons) the level, near the hearer's location, above which complaint is liable to occur (40 phons), corresponds very nearly to 1 loudness unit.

(e) Interception of Vibration Transmitted from Core to Tank

The provision of some kind of barrier or absorber for intercepting or attenuating the vibration transmitted from core to tank and thence radiated as noise, has sometimes been proposed.* In a normal transformer, transmission takes place mainly by two paths, namely by the contact of the core with the bottom of the tank, and thence to the sides; and by direct transmission through the oil. Vibration can be transmitted through leads from core to tank, but unless the leads are unusually stiff the amount of vibration transmitted can be neglected.

To ascertain the relative amounts of vibrational energy transmitted by the two main paths, an experiment was carried out with the 60-kVA 3-phase transformer already referred to. It was first tested in the normal condition, i.e. with the core resting directly on the bottom of the tank. The core was then placed on resilient supports designed† with a sufficiently large attenuation to ensure that the vibration transmitted through them was negligible. The noise was again measured at the same flux density, with the result shown in Table 7.

Table 7

Effect of Mounting Oil-Immersed Core on Resilient Supports: 60 kVA, 3-phase Transformer Frequency = 50 c./s.

Condition	Phons
Without resilient supports ..	56
With resilient supports ..	52

From a consideration of the laws of audition, it appears that the sound energies transmitted by the two paths are of the same order of magnitude. Hence, although the use of resilient supports between core and tank does not alone effect a substantial reduction in noise, the supports would become of great importance if a considerable amount of attenuation could be introduced into the oil path.

A theoretical study was therefore put in hand with a view to obtaining some guide as to the type of barrier or absorber that would be most effective. It soon became apparent that a compliant rather than a stiff or massive barrier was required.‡ To verify this, a 1-in. thick hardwood barrier for insertion between the tank wall and core of the 10-kVA single-phase unit used for earlier experiments was made, so as to enclose the transformer on all four sides. The core was resiliently mounted. Noise measurements without and then with the barrier in position showed a reduction in level of not more than 2 phons.

* For example, British Patent No. 380136—1932.
† A. J. King: *Engineering*, 1937, **144**, p. 296; 1938, **146**, pp. 124 and 198.
‡ British Patent No. 501016—1939.

The theoretical and practical merits of different possible forms of compliant absorbers were then examined, particularly in regard to materials capable of withstanding hot oil satisfactorily. A set of hollow air-filled absorbers with thin sheet-metal sides was made up for trial with a small transformer that was available. The results were promising, but, owing to the difficulty of making satisfactory noise measurements and analyses at the very low levels obtained, it was decided to construct a set of absorbers for the 60-kVA 3-phase transformer previously mentioned. At the same time a tank with cooling tubes, of standard design but with slightly increased dimensions to accommodate the absorbers, was constructed, including the additional fittings required. These consisted of an iron plate resting on the bottom of the tank on which were mounted the resilient supports for the core and suitable guides into which the absorbers could be inserted. The construction of the absorbers was modified to some extent as a result of the experience gained. Sheet metal was discarded in favour of cellulose sheet. It was found convenient to make the absorbers in two sections, mounted one above the other. Thus to surround the transformer on all four sides required 8 sections. Apart from constructional convenience, this sub-division had the advantage that in the unlikely event of the failure of a section, the attenuation would not be greatly impaired and the oil level in the tank would fall by only a small amount. In view of the resilient mounting of the core, movement at its upper end while being transported was limited by a simple fitting. The principle of the scheme is shown diagrammatically in Fig. 3.

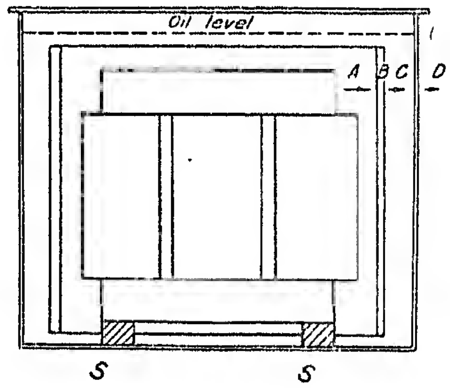


Fig. 3.—Diagrammatic illustration of resilient absorbers and mounting in a 3-phase transformer.

A. Large pressure pulsations in oil (incompressible) due to core vibration.
B. Absorber yielding readily to pressure pulsations.
C. Reduced-pressure pulsations transmitted by absorbers to outer layer of oil and tank side.
D. Reduced sound pressure radiated by tank side.
S. Resilient supports.

Noise measurements and analyses were then made over a range of flux densities and it was found that a substantial reduction in noise had been obtained. Noise measurements were next made to ascertain the effect of (i) the clearance between the lower edge of the lower absorber section and the bottom of the tank, and (ii) the depth of oil above the upper edge of the upper absorber section. This having been ascertained, suitable clearances were chosen, having regard to the oil expansion which accompanies the normal temperature rise of the transformer, and the need for avoiding any constriction of the oil flow. As the absorbers are located substantially in the neutral plane of natural oil circulation, it was anticipated

that the oil circulation, and hence the temperature rise of the transformer, would not be appreciably affected by the presence of the absorbers. Temperature tests with a power input equal to the total full-load losses were then carried out, with the absorbers first in position and then removed. It was found that the temperature-rises above ambient temperature for the steady state did not differ by as much as 1 deg. C. for the two conditions.

Complete noise measurements and analyses were then made for the oil level chosen and also with the absorbers removed, the oil level being kept constant. The results are shown in Fig. 4, from which it is seen that the absorbers effect a reduction of the order of 30 phons. The levels reached with the absorbers in position are considerably lower than would be necessary in practice, and it was not possible to make satisfactory noise measure-

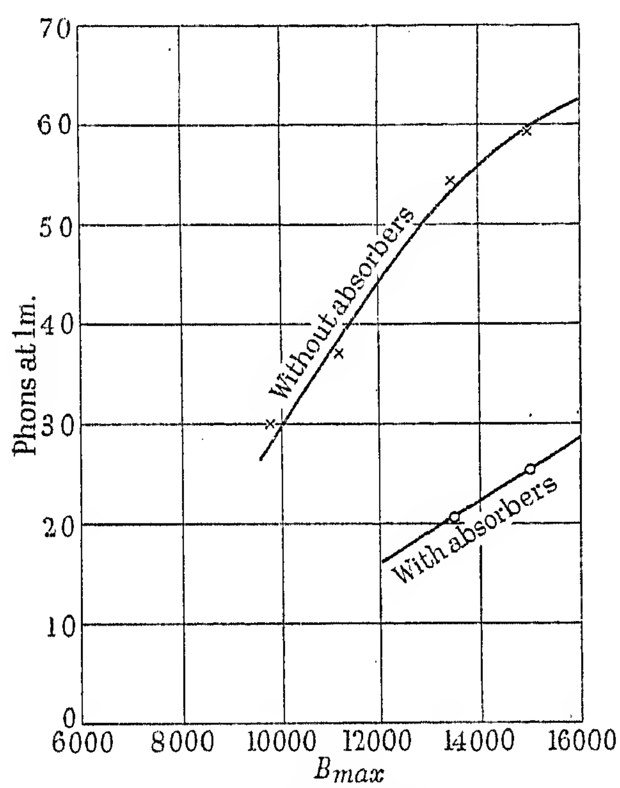


Fig. 4.—Reduction of noise by the use of vibration absorbers: transformer 60 kVA, 3-phase, 50 c./s.

ments below B_{max} = 13 000. However, the significance of the results lies in the fact that reductions of the order of 30 phons are rendered practicable by the use of absorbers.

It was then decided to treat a 400-kVA 3-phase distribution transformer on the same lines. A set of absorbers and a naturally cooled tank with the necessary additional fittings were constructed. Hand-operated off-circuit tap-changing gear was mounted above the transformer and the total height was such that the absorbers were subdivided into four sections one above the other, each 15 in. deep, giving 8 long and 8 short sections. The result obtained is shown in Fig. 5, from which it is seen that at normal flux-densities a reduction in E.L. of 25 phons or more is secured, the E.L. with the absorbers in operation being approximately 40 phons, i.e. sufficiently low to remove cause for complaint, even in close proximity to a dwelling house. Noise analyses were also made, both at an applied frequency of 50 c./s. and at frequencies above and below this value, and the effect of the absorbers on the E.L. of each component of the noise was

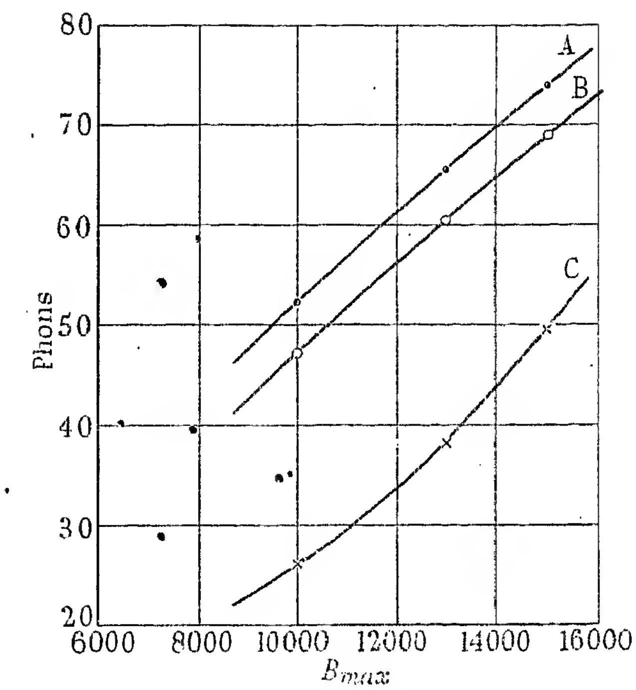


Fig. 5.—Noise reduction on 400-kVA distribution transformer by means of internal absorbers.

A. Transformer of standard design.
B. Experimental transformer with resilient mounting but without absorbers.
C. Experimental transformer with resilient mounting and absorbers.

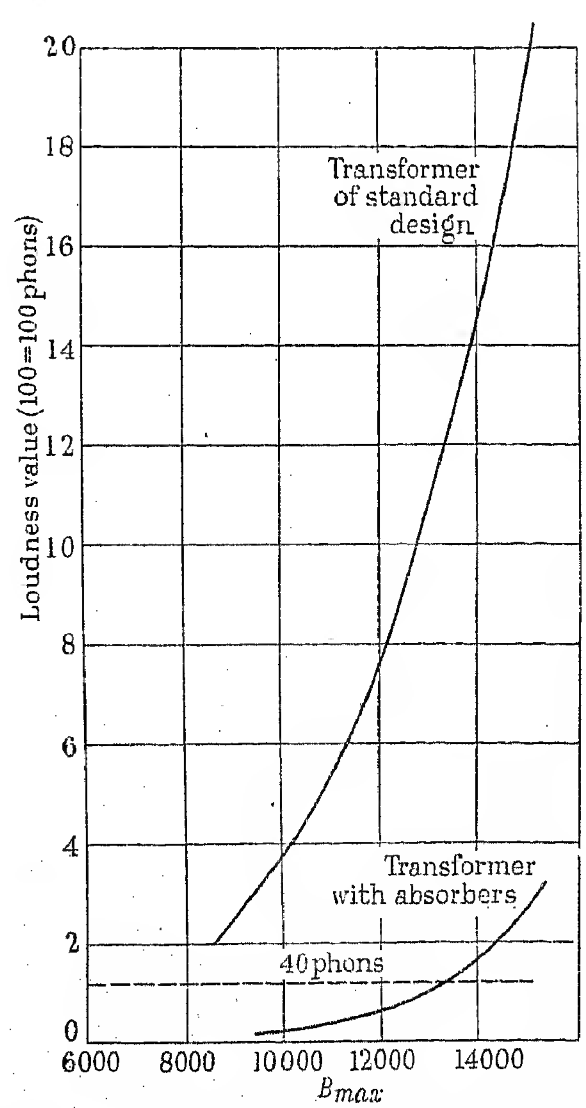


Fig. 5A.—Noise reduction on 400-kVA distribution transformer by means of internal absorbers.

traced. It was evident that the attenuation was influenced to a minor extent by a partial resonance occurring in the vibrating system at a frequency below 100 c./s., and if it had been important to secure further reduction in E.L. a modification could have been made to this end. A comparison of a 400-kVA transformer of standard design with one fitted with absorbers is given in Fig. 5A on a loudness basis, i.e. as perceived by a normal hearer.

To ascertain whether any leakage or other deterioration developed with time as a result of the temperature cycle normal to the operation of a distribution transformer, an absorber section was immersed in a tank of oil containing a heating resistor. Power was switched on each morning and off each evening. During the day the temperature reached 80° C. The test was continued for 10 weeks, during which time no deterioration was observable. Many absorbers, of different types and sizes, have been constructed and tested during the investigation and, apart from one case of accidental damage during handling, no case of failure has occurred.

To obtain further evidence regarding the possible deterioration of absorbers or other unforeseen effects which might occur in service, the complete 400-kVA transformer was subjected to a repeated temperature cycle. The power input was adjusted to correspond with more than full-load losses and was switched on each morning. The maximum oil temperature reached at the end of the day was 70° C., the power then being switched off. The cycle was repeated on 60 days, after which an examination was made. No deterioration was observable.

A point which would need consideration with large transformers is the static oil-pressure under which the lower absorber sections would operate owing to the increased head of oil. Some experiments were carried out with an absorber section, immersed in water in a closed tank provided with plate-glass windows, through which the behaviour of the absorber section could be observed. Means for varying temperature and hydrostatic pressure were provided. It was found that the behaviour of the absorbers under conditions corresponding to the largest transformers was satisfactory.

(f) Tank Construction

We may consider here constructional modifications or attachments which may be incorporated in the tanks of oil-immersed transformers for the purpose of noise reduction.

A normal transformer tank has many possible modes of vibration, the corresponding natural frequencies extending over a large part of the audible frequency range. As we have seen, the impressed vibratory frequencies extend from 100 to perhaps 1 400 c./s. in steps of 100 c./s. To estimate the natural frequencies of a tank would be a very complex and uncertain matter, so that to attempt to ensure that impressed and natural frequencies are kept sufficiently far apart to avoid complete or partial resonance would be impracticable. Adding moderate amounts of stiffness or mass to the walls of a normal tank may shift the natural frequencies nearer or farther from the impressed frequencies and may therefore either increase or decrease the contribution of particular components without greatly affecting the noise as a whole. The possibility of considerably increasing the mass and introducing some damping as well to blunt the resonances by covering the tank sides with a layer of concrete was considered and thought worth a trial. Experiments were therefore carried out with a tank suitable for a 60-kVA transformer and fitted with a detachable radiator instead of the usual rows of cooling tubes. Iron projections were welded to the outside of the tank to afford means of rigidly attaching concrete to the sides. Noise measurements and analyses were made with and without the radiator attached and before and after applying a 2-in. layer of concrete. From the analyses, the low-frequency components were found to have been reduced and others increased, and the change in quality of the noise was evident aurally. There was no evidence that the addition of the concrete had increased the damping. The noise measurements showed no resultant decrease in E.L. exceeding 1 phon at any flux density.

It has been proposed to reduce the radiation of noise from transformer tanks by providing external barriers or false sides resiliently mounted on the tank.* It is, of course, necessary in such a case to effect cooling by a separate radiator piped to the tank or by other external means. To obtain a substantial reduction, e.g. 20 phons, by this method would require the fulfilment of two conditions. First, the amplitude of vibration of the false sides would need to be reduced to the order of one-tenth that of the normal tank sides, which would require very effective resilient mounting of the false sides. Secondly, the tank would need to be so completely covered by the false sides that the acoustic energy emitted would be reduced to one hundredth of that emitted without the false sides. With this object in view the false sides are made to extend continuously round the tank, but it is apparently considered that there is no need to cover the lid, which is in intimate contact with the body of the tank. The propagation of sound waves of a few hundred cycles per sec. does not proceed in accordance with optical laws, i.e. such low-frequency sound waves are by no means highly directional but spread out readily in all directions. Hence sound will not be emitted from the top of a tank purely vertically but would be heard even though none were emitted from the sides. The authors would expect that complete enclosure would be required to secure a reduction of 20 phons. Forrest† reports a reduction of approximately 10 phons when a method of this type (no details are given) is applied to a 20 000-kVA unit. In most cases this result would be inadequate, but if the principles of enclosure and isolation were carried to their logical conclusion much greater attenuations would be available. This is discussed later, in Section (5)(*c*). It has been suggested that a useful noise reduction can be obtained by "lagging a tank with sound-absorbing material." If by this is meant the application of soft material of low reflection-coefficient directly to the tank surfaces, the proposal seems to rest on confusion of the properties of absorption and attenuation. The material would not function in virtue of its low reflection-coefficient and an inconveniently large amount of it would be required for a useful attenuation. Neither would a hard

* British Patent No. 444129—1936.
† *Beama Journal*, 1939, **44**, p. 51.

massive material normally useful for sound attenuation be effectual if used in this way, since it would readily transmit the vibration imposed by the tank side.

(5) NOISE LIMITATION BY EXTERNAL MEANS

(a) General

In the previous Section, means whereby the acoustic output of the source can be controlled have been examined. In the present Section we shall consider how the E.L. of the noise reaching the hearer can be controlled by the introduction of attenuation in various forms between the source (i.e. the complete transformer as a unit) and the hearer. In practice, attenuation is often provided by circumstances which arise out of considerations other than noise. It is clearly desirable to utilize such attenuation, supplementing it where necessary by additional attenuation artificially introduced. It is therefore important that methods of predicting the noise reduction due to external attenuation should be available when an installation is being planned, so that it can be ensured that sufficient attenuation is provided and also that the practical merits of alternative proposals may be compared. In general, the accurate prediction of the noise reduction is not a simple matter. One reason is that we are dealing with complex sounds, i.e. sounds containing components of different frequencies. The transmission coefficients of partitions and the absorption coefficients of sound-absorbing materials vary with frequency, so that the several components of a noise are attenuated by different amounts. In general, after having suffered attenuation, the composition or tone structure of a noise will not be the same as before attenuation, an exception being when the noise consists of a single tone. Strictly, it is therefore necessary when predicting the noise reduction to know the composition of the acoustic output of the source as well as its E.L., to estimate the attenuation suffered by each component, and then to estimate the resulting E.L. of the attenuated components.* The detailed discussion of this aspect of the subject is beyond the scope of the present paper.

The authors' colleague, Mr. S. W. Redfearn, has carried out a comprehensive mathematical examination of the attenuation of sound afforded by structures of various kinds, which it is hoped to publish shortly. The conclusions reached have been found to be in accord with the results of experimental work and with practical experience. It is proposed to give here a summary of the conclusions reached as to the practical efficacy of different methods of introducing attenuation. We shall only consider incidentally the attenuation of that part of the sound which is transmitted by contact between a transformer and a structure. Cases occur where the whole of the sound is transmitted in this way, there being no parallel air path—e.g. the transmission of sound between two rooms in the same building, one of the rooms having no windows or other vents. This subject has been fully discussed elsewhere,† and, as far as transformers are concerned, practically any desired amount of attenuation can be introduced by providing suitably designed resilient supports. It is necessary to emphasize that the indiscriminate insertion of resilient blocks, as opposed to the provision of supports designed with a full appreciation of the dynamic properties of the material and the conditions of operation, may not only fail to reduce vibration transmission but may actually increase it. Outdoor transformers usually rest on a concrete foundation and it is not as a rule necessary to fit resilient supports. The foundation block is seldom attached to a surface that can radiate sound effectively, and appreciable vibration transmission through the ground is unlikely unless the transformer is located very close to house property. In one case of complaint within the author's experience, it was found that the transformer foundation had been keyed to a brick wall which was continuous with the wall of a house. Some quite ineffective resilient supports had been fitted. The substitution of adequately designed supports proved to be the remedy.

* A. J. King: *Engineering*, 1937, **144**, p. 296; 1938, **146**, pp. 124 and 198.

† A. J. King: *loc. cit.*

(b) Effect of Distance

The distance between the source and the hearer generally in itself makes some contribution towards the limitation of transformer noise. The rate at which the E.L. falls off with increase in distance depends on a number of factors. Consider first the simplest possible case, namely that of a point source emitting a single tone of 1 000 c./s. in free space, i.e. completely spherical radiation. Neglecting energy absorption in the atmosphere, which is inappreciable at audio frequencies and moderate distances, the total radiated energy is constant at all radii, so that the energy per unit area varies inversely as the square of the radius and the acoustic pressure inversely as the first power of the radius. Hence if the intensity level at radius R is

$$20 \log \frac{P}{0 \cdot 0002}$$

the intensity level at radius $2R$ will be

$$20 \log \frac{P}{0 \cdot 0004}$$

a difference of 6 db. Since at 1 000 c./s. the intensity level is equal to the E.L., the E.L. at radius $2R$ will be 6 phons less than at R. In other words, each time the distance from the source is doubled, the E.L. falls by 6 phons, until, of course, the threshold-intensity level, corresponding to a pressure of $0 \cdot 0002$ dyne per cm^2, is reached, after which the sound becomes inaudible.

With tones of frequency other than 1 000 c./s., the equal-loudness relations* operate. This causes the E.L. of a low-frequency tone, e.g. 100 c./s., to fall off more rapidly with distance than that of a 1 000-cycle tone, i.e. the reduction in E.L. for a doubling of the distance would be more than 6 phons. However, for frequencies of 300 c./s. and upwards the figure of 6 phons is substantially correct.

With the complex sounds emitted by a transformer, not only do the equal-loudness relations operate in the way indicated but the law of combination of the ear, which varies with level, enters into the matter, so that the estimation of the effect of distance becomes less simple. Further, a transformer cannot be considered a point source for distances which are not large compared with

* B. G. Churcher and A. J. King: *Journal I.E.E.*, 1937, **81**, p. 57.

its overall dimensions. Again, the radiation of sound cannot be completely spherical owing to the presence of the ground, except in the unlikely case of the ground having unity absorption coefficient. Some reflection from the ground is always present, so that the variation of E.L. with distance is modified by this factor. However, in practice E.L. measurements on transformers at distances greater than the largest dimension do not show any marked divergence from the value of 6 phons for a doubling of the distance, so that the simple rule suffices for most practical purposes.

(c) Effect of Enclosure

We may first note some practical considerations. The need for the enclosure of a transformer for the purpose of noise limitation is, in general, confined to outdoor transformers. It would seem that the only case where enclosure of an indoor transformer would be needed is where quiet is required in the room in which the transformer is located, an unusual requirement. Transmission of noise from the room in which the transformer is located to another room in the same building can be in the form of structure-borne noise or air-borne noise or a combination of both. Structure-borne noise can be dealt with by the provision of a correctly designed resilient mounting for the transformer, as previously mentioned. In one case of wholly structure-borne noise within the authors' experience, the E.L. in a room used as an office immediately adjacent to a transformer chamber containing two 10 000-kVA units was reduced from 80 to 40 phons by mounting the transformers on resilient supports designed to give that reduction. Air-borne sound emitted from a transformer chamber requires the introduction of sound attenuation in air ducts or vents of a kind that does not unduly restrict air flow. If the chamber is substantially built, e.g. of brick or concrete, the sound energy passing directly through the walls is usually negligible compared with that emitted by the other paths mentioned. Hence where enclosures are provided for noise limitation, they must usually be suitable for outdoor use. Not only must the enclosure be weatherproof but the oil-level gauge and the temperature indicator must be visible, and the emptying valve and the filter valves must be accessible. Where connection is made by cables and junction boxes, which is usual for voltages up to 11 kV and frequently up to 33 kV, precautions are necessary to limit the amount of vibration transmitted from the tank along the cables to the enclosure. Some form of kiosk may suffice for small, moderate-voltage transformers. Where on-load tap-changing gear is mounted on the transformer tank, and especially where space for access has to be allowed between tap-changing gear and enclosure wall, and where an oil conservator has to be accommodated, the enclosure is considerably increased in size. With high-voltage transformers, usually of large output, where cables and junction boxes cannot be used on the high-voltage side and bare conductors and bushings inserted in the enclosure wall or roof are involved, the scale of the enclosure is much increased and a brick or concrete building is called for. Further, there is the problem of the cooling of an enclosed transformer.

We can now consider the acoustical aspect of enclosure. In recent years a detailed study has been made at the National Physical Laboratory* and elsewhere of the attenuation of sound in its passage through walls or partitions of various types. Briefly, the attenuation is measured by inserting a partition of the material into an opening between two rooms entirely isolated acoustically from one another, a source of sound of the desired frequency being operated in one of the rooms. The acoustic pressure on either side of the partition is then measured by calibrated microphones, and the attenuation in decibels is given by $20 \log P_1/P$. The most important conclusion to be drawn from these researches is that over a wide range of materials and thicknesses the attenuation is a function of the mass per unit area. Thus at 200 to 300 c./s., frequencies with which we are concerned, the attenuation varies from 12 db. for a partition weighing $0 \cdot 5$ lb. per sq. ft. to approximately 49 db. for one of 50 lb. per sq. ft. This applies to materials such as building board, plate glass, wood and brickwork. From theory it is to be expected that if attenuation depended on inertia (mass per unit area) only, the attenuation of a partition for a doubling of thickness would be increased by 6 db. Experimentally this figure is found to hold approximately. Thus if a $4\frac{1}{2}$-in. brick wall has an attenuation of 47 db. at 200 to 300 c./s. a 9-in. wall will have a value of approximately 53 db. Also, if the frequency is doubled, the attenuation is increased by 6 db. Hence if a transformer be placed in an enclosure the walls and roof of which have sufficient mass per unit area, substantial noise reduction is to be expected. However, to obtain the benefit of the attenuating effect of the enclosure it is essential to prevent the transmission of vibration by direct contact between transformer and structure by the provision of an adequate resilient mounting. Also, the presence of vents or other openings can seriously impair the attenuation of an enclosure. Space does not permit a detailed discussion of this matter, but a simple example will illustrate the order of the effect. Consider a partition giving an attenuation of 40 db. The energy density on the incident side is 10 000 times that on the emergent side. If now holes are made in the partition having a total area equivalent to 1 % of the area of the partition the average energy-density on the emergent side will be increased 100 times. Thus the attenuation will be reduced from 40 to 20 db. This effect clearly has an important bearing on the enclosure of naturally-cooled transformers.

Another acoustical effect which arises when a transformer is placed in an enclosure is what may be termed the "build-up" effect. The absorption coefficients of brick, concrete and metal surfaces are very low; of the order of a few per cent. Thus with the usual brick or concrete walls 97 % or more of the sound energy radiated by the transformer tank is reflected from the enclosure surfaces and multiple reflections take place. The sound energy is conserved rather than dissipated, so that the average intensity-level at a given short distance from the transformer is greater with the enclosure present than with it absent. This "build-up" effect, which can be expressed in decibels, offsets the attenuation effected by the enclosure. This is illustrated diagrammatically in Fig. 6, where (*a*) shows a transformer T mounted on

* J. E. R. Constable and G. H. Aston: *Philosophical Magazine*, 1937, **23**, p. 161.

resilient supports on a substantial foundation. When the transformer is excited, sound waves are emitted from the sides and top. Suppose the intensity level, in decibels, of a particular component is X near the tank side. When the enclosure is placed in position [Fig. 6(*a*)], the internal intensity level will increase to $(X + B)$, where B is the "build up" effect. The intensity level immediately outside the enclosure will be $(X + B - A)$, where A is the attenuation of the enclosure for that frequency. Redfearn's researches have led to a method of estimating the magnitude of the "build up" effect. It has been found that in practical cases this can reach considerable values. If it is desired to utilize A more fully, B can be reduced by increasing the total absorption present inside the enclosure by adding suitable sound-absorbing material, the required amount of which for a given reduction in B can be estimated. In planning for a given overall attenuation, the values of B and A chosen should clearly be determined by consideration of cost, provided no structural limitations supervene.

We have seen that the attenuation of a wall is increased

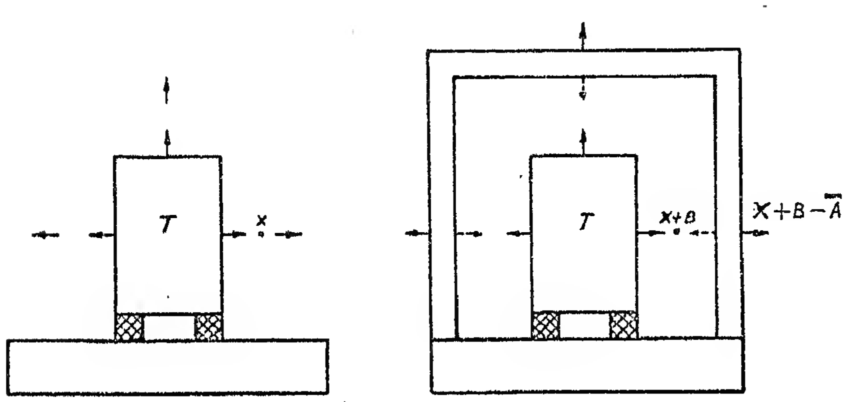


Fig. 6.—Diagrammatic illustration of the effect of enclosing a transformer.

by approximately 6 db. only when its thickness is doubled. If, instead of doubling the wall thickness, we use two independent walls of the same thickness or a double wall, the attenuations are additive provided certain conditions are met. These are that there shall be negligible mechanical coupling between the two walls by ties or other solid connection, and that the air space is large enough to make the air coupling negligible. Thus attenuations of the order of 100 db. are theoretically possible but, apart from such high values being rarely required, other sound-leakage paths would generally vitiate their effect. It may be noted* that no advantage over a single solid wall of the same mass per unit area is obtained by the use of hollow bricks.

The way in which the foregoing principles may be applied to practical cases will be illustrated by a few examples. The case of a water-cooled transformer or a transformer with a separate oil cooler is comparatively simple, owing to there being no need to provide for the dissipation of a large amount of heat by air circulation. We have only to deal with that part of the heat dissipated by the plain tank. The thermal resistance of a brick or concrete enclosure can be approximately estimated, and it will be found in general that the equilibrium temperature reached by the air within the enclosure is not unduly high, even though no vents whatever are provided. A case of the enclosure of a large transformer, planned in 1936, may be quoted. The transformer is of 75 000 kVA, 3-phase, and is installed immediately outside a power station. Cooling is by forced oil circulation, the oil being passed through an external water cooling system. The object of enclosure was to ensure that the noise level at house property in the vicinity was not materially increased, particularly at night. At the time no information was available on the noise levels of transformers of this size, and to ensure a margin a lower flux-density than normal was specified. For structural reasons the walls of the transformer house were made of brickwork at least 14 in. thick, a thickness of 18 in. being used in some parts. The roof was of 6-in. concrete. It was anticipated that with such a large transformer the 100- or 200-cycle components would be predominant. At these frequencies an 18-in. brick wall may be expected to give from 45 to 50 db. attenuation. To enable this to be realized, doors providing for the removal of the transformer from the house would have had to be both very large and of the same order of mass per unit area as the brickwork. To avoid this it was decided to dispense with main doors and to brick-up the transformer after installation. Such small doors as were necessary for access were made to have the required attenuation by a double construction, two iron doors with rubber seatings being provided, with an air space between. The transformer, weighing approximately 100 tons, was mounted on rubber resilient supports designed to have an attenuation of over 40 db. at 100 c./s. Connection from the transformer to the oil cooler, located outside the transformer house, was made by flexible metallic piping. As the cable connections emerged by ducts in the ground, no special precautions against vibration transmission were necessary. Noise measurements on a transformer while on test in the factory gave 79 phons at a distance of 1 m. at rated voltage. After installation an E.L. of 96 phons in the transformer house was observed, the increase of 17 phons being due to the "build up" effect. This figure was in good agreement with calculation. Measurements immediately outside the transformer house gave a value of 62 phons, but it was obvious that this figure included some station noise, much of which was of similar composition. Hence the value attributable to the transformer alone is less than this. The reduction due to the walls is therefore certainly more than 34 phons. Measurements at greater distances from the transformer house were less reliable, as the transformer noise was still less distinguishable from station and other noise. The result was therefore considered adequate. Increasing the net attenuation of the enclosure by the addition of sound-absorbing material in order to reduce the "build up" effect of 17 phons was considered, but, in view of the results, felt to be unnecessary. However, in retrospect it is now (1939) clear that a more economical solution would have been obtained by designing the transformer for normal flux-density and utilizing some of the resulting saving to provide sound-absorbing material in the enclosure which, by reducing the "build up" effect, would more than offset the increased free-space noise emission of the transformer.

Where small naturally-cooled distribution transformers

* *Philosophical Magazine*, 1937, **23**, p. 161.

are installed in kiosks, on account of accommodation being required for switchgear or other apparatus the kiosk often affords a substantial amount of attenuation. Sheet steel $\frac{3}{16}$ in. thick, if not perforated with holes, gives an attenuation of approximately 32 db. at 300 c./s. provided no important mechanical resonance is present. Owing to the size of the kiosk being larger than is required to accommodate the transformer alone, its surface may be considerably greater than that of the tank and cooling tubes, so that, owing to the low thermal resistivity of steel, a considerable amount of heat can pass directly through the kiosk walls without an unduly large temperature-drop. The total cross-section of the ventilating louvres provided for cooling need not, therefore, be large. The cooling aspect is further eased when the transformer carries full load for a few hours only each day, as is often the case, the thermal capacity limiting the temperature-rise. The total cross-section of the vents may therefore be insufficient to impair greatly the attenuation. The presence of vents also provides a certain amount of internal absorption, which limits the " build up " effect. Some measurements on a 350-kVA distribution transformer installed in a kiosk gave a reduction in E.L., due to the presence of the kiosk, of 25 phons.

The enclosure of large naturally-cooled transformers, especially those operating at fairly high load factors, makes the problem of cooling less simple. A brick or concrete building rather than a kiosk may be called for on account of size. The thermal resistance of a brick or concrete building without ventilation is so great that only a small fraction of full-load losses could be dissipated through its walls without a prohibitive temperature rise. The building may be required for other reasons besides noise limitation, but only a moderate noise-reduction is obtainable without special measures. A case of a 10 000-kVA naturally-cooled transformer installed in a substation in a residential district may be cited. The building was a substantial brick structure. The cooling air entered through numerous louvres in double iron doors, of sufficient size for the transformer to pass through, and emerged through a horizontal duct of ample cross-section in the roof of the building. The E.L. inside the substation was 84 phons and immediately outside the louvred doors 70 phons, giving a gross reduction of 14 phons. This low figure is of course due to the large cross-section of the ventilating openings, since the walls and roof of the building would be capable of a reduction of the order of 40 phons. Immediately outside the nearest house the E.L. was 50 phons, which was considered to be undesirably high, a figure of 40 phons or less being more desirable. To obtain the extra 10 phons reduction a hollow brick wall was built internally extending to the roof and opposite the large louvred doors, vertical side ducts of ample cross-section being formed for the entrance of the cooling air. Measurements showed that immediately outside the louvred doors the E.L. had fallen to 56 phons and, at the house, to 37 phons. Thus the gross reduction due to the building had been increased to 28 phons, which was quite adequate for the particular case although less than the possible figure of 40 phons. If it is desired to realize such a figure, it is necessary to increase the attenuation along the air ducts and other sound-leakage paths to this order of magnitude. Sufficient attenuation in the resilient mounting presents no difficulty. The attenuation along ventilating ducts can be increased as much as is required by a suitable disposition and quantity of sound-absorbing material. In one instance the authors have obtained a reduction of 20 phons in a length of 9 in. for a fairly high-frequency sound. However, the attenuation per unit length of duct is closely related to the pressure drop per unit length. With highly attenuating ducts the pressure head necessary to circulate the required amount of air may be greatly in excess of that which is available from the convective flow by which most of the heat from naturally-cooled transformers is dissipated. If there is no other objection to its use, the required amount of air can be made to flow by introducing a fan, located preferably inside the building, so that the noise from it is suppressed by the duct attenuation.

It has now become general practice to build large distribution transformers with one or more separate radiator units, piped to the tank. This gives an opportunity of dealing with noise by enclosing the tank of the transformer within a building without vents and installing

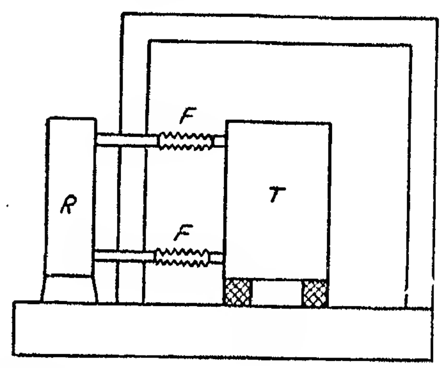


Fig. 7.—Diagrammatic illustration of a transformer in an enclosure with external radiator.

T = transformer, resiliently mounted.
R = radiator.
F = flexible pipe connections.

the radiators outside, as shown diagrammatically in Fig. 7. Owing to the very limited cross-section of the openings between radiator and tank, it is to be expected that the vibratory oil pressure acting on the inner radiator surfaces, and hence the sound emitted, will be small compared with that acting on the tank walls. Aural impressions confirm this. Some careful measurements on a small transformer tank fitted with a detachable bolted-on radiator indicated that the acoustic energy emitted by the radiator was about 20 % of the whole. If without further steps the tank were enclosed so that it could radiate no sound, the level due to the radiator alone would be only about 7 phons less than that due to the unenclosed tank and radiator. Hence, in general, attenuation must be present in the connection between tank and radiator if useful noise-reductions are to be obtained. Transmission of vibration appears to take place along the pipe rather than through the oil,* so effective results can be obtained by using a length of piping of flexible material capable of withstanding hot oil, or even the flexible metallic tubing often employed. The flexible connection reduces vibration transmission both to the radiator and to the enclosure. Mason† has applied a sound-attenu-

* J. E. R. Constable: *Proceedings of the Physical Society*, 1938, **50**, p. 360.
† *B.T.H. Activities*, July–August, 1938.

ating box to a 500-kVA transformer with separate radiator. The radiator was connected by flexible tubing and the tank resiliently mounted. The box is stated to be built of sound-insulating material, but the nature of the material is not indicated. A reduction of 18 phons is obtained, but it is pointed out that larger reductions are possible. Large transformers with separate radiators are sometimes cooled by air blast directed on to the radiators, the air blast being out of action at periods of light load. Where it is necessary to limit the noise of such units, attention has to be given not only to the transformer noise but also to any noise that may arise from the fans or air jets.

In built-up districts where space for transformers or kiosks is restricted, transformers are sometimes installed in brick-lined pits, suitably ventilated. If, helped by low load factor, the vents need be of small size only, a useful noise reduction, compared with the noise associated with an outdoor transformer, is to be expected. To reduce installation costs, the suggestion of burying the transformer tank directly in the ground has been made. If this were practicable, noise could be completely suppressed. However, the thermal conditions are such as to make the scheme impracticable for any but very small transformers. If, for the sake of argument, we assume a transformer tank of spherical shape, it can be shown that the thermal conductance to an infinite mass of earth (i.e. neglecting the ground surface) is analogous to the electrical capacitance of a sphere in infinite space. The conductance increases as the radius of the sphere. However, the energy loss will increase roughly as the cube of the radius, so that as the size of the transformer is increased, the amount of heat to be dissipated soon overtakes the amount of heat it is possible to conduct away for a given temperature-rise. Hence the proposal has not come into general use.

(d) Use of Barriers

A method of obtaining external attenuation is to use a barrier, e.g. a brick wall, between the transformer and the location at which it is desired to limit the noise. Unless the barrier is of infinite height and width, the attenuation which it produces at frequencies of a few hundred cycles per second can never approach that which it would afford if it formed one side of a complete enclosure. At these frequencies diffraction of the sound takes place round a barrier of finite dimensions. Redfearn's mathematical investigation of this subject, which has been confirmed experimentally, shows that the attenuation obtainable depends upon a number of factors, the most important being the effective height of the barrier above a line joining the source to the hearer and the nearness of the source and hearer to the barrier. For example, take the case of a transformer of mean height 5 ft. situated 24 ft. from a 2-storey dwelling house. The attenuation with distance and without a barrier would be approximately 15 db. With any but a small distribution transformer, this attenuation may result in a noise level in excess of 40 phons. Table 8 shows the estimated effect of interposing barriers of 10 ft. or 15 ft. height at a distance of 4 ft. from the transformer. Values are calculated for the upper and lower floors of the house and for 100 and 300 c./s., the frequencies with which we are most concerned.

The attenuation values shown in Table 8, which are additional to that due to distance, may be just sufficient to bring the E.L. below 40 phons. However, it should be noted that to obtain these values the width of the barrier must be such as to put the house completely within the sound shadow. The same object may be attained by making the barrier three-sided. It is seen from the Table that the attenuation to the upper floors is less than to the lower, whereas usually quieter conditions are desirable for the upper than for the lower floors. Further, it is seen that a 50 % increase in barrier height increases the attenuation by only 4 db. Also, the presence of a barrier increases the E.L. in the opposite direction, which is a limitation to its general usefulness. The general conclusion is that a barrier may be useful in particular cases, where a small attenuation in one direction only is required. However, for large attenuations and especially for attenuation in all directions, it is uneconomic.

Table 8

Barrier height	Floor	Frequency	Attenuation
ft.		c./sec.	db.
10	Ground	100	10
10	Ground	300	15
10	Upper	100	7
10	Upper	300	10·5
15	Ground	100	14
15	Ground	300	18·5
15	Upper	100	11·5
15	Upper	300	16

(e) Penetration of Noise into Buildings

The final attenuating factor in the sequence from source of noise to hearer in transformer-noise problems in residential districts is the attenuation provided by a house. The difference between the intensity incident upon the outside of a house and that within a room depends upon the area of the opening of a window and the amount of acoustical absorption within the room. Where windows are closed the attenuation depends on the total window area and thickness of glass. Redfearn's investigation has covered these questions; and his conclusions, which will be given in detail elsewhere, are that, according to the amount of absorption present and the window-opening area, attenuations up to 15 db. are possible. It is fortunate that where most attenuation is needed, i.e. in bedrooms, the absorption is usually greater than in other rooms, and values of 10 db. are found in practice for open windows, which must generally be assumed. For closed windows, the attenuation may rise to 15 or 20 db.

(6) CONCLUSIONS

The paper describes the many factors which determine the noise emitted by a transformer installation, from

which it is seen that there are many theoretically possible methods of abatement. However, owing to limitations arising out of electromagnetic, thermal and constructional considerations, all of which are subject to the important question of cost, comparatively few of the possible methods are practicable. Recent research, both theoretical and experimental, together with practical experience, has placed the subject on a quantitative basis. This not only gives an assurance that the noise can be limited to the desired figure but means that the results obtainable by alternative methods can be predicted, and this is the first essential to ascertaining the most economic method.

In the problem of noise in residential districts, there are always two helpful factors present in some degree, namely distance and the attenuation afforded by a house. What is necessary beyond this to ensure at the hearer's location a reasonable degree of comfort in respect of noise may be effected by one or other of the methods discussed. Where a substation building or other enclosure is required for reasons other than noise limitation, consideration of the design of the building from an acoustical standpoint may indicate a comparatively simple and inexpensive solution. If a building is not necessary apart from the question of noise, the method of noise limitation by absorbers within the transformer tank has many points in its favour. The transformer and the tank, apart from a few internal fittings, are of standard design and no special installation requirements arise. No interference is occasioned with normal methods of cooling or with electrical connections. Although a tank larger than normal, with additional oil, is required, the extra cost and space occupied are small compared with the cost of, and land required for, a building. The absorber method is applicable with any form of cooling and there is apparently no limit in regard to size of transformer that can be dealt with. The other method applicable to large transformers is that of enclosing the tank and coupling it flexibly to outside radiators. For large noise-reductions the building needs to be substantial, and a very large building is required for large high-voltage transformers.

The foregoing discussion of the problem of transformer noise, from source to hearer, illustrates the importance of taking a comprehensive view of the subject, comprising, in addition to normal engineering considerations, acoustical principles which are accepted in physics but which are not widely known in engineering. It is only by taking a broad view that misdirected effort may be avoided and the future progress of the subject promoted.

(7) ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of several of their colleagues of the staff of the Research Department of the Metropolitan-Vickers Electrical Co., Ltd., particularly Mr. A. S. Ennis and Mr. S. W. Redfearn. They also wish to record their appreciation of the co-operation and helpful criticism extending over several years of Mr. A. G. Ellis and members of the staff of the Transformer Engineering Department. Finally, the authors' thanks are due to Mr. J. S. Peck and Dr. A. P. M. Fleming, Directors of the Company, for permission to publish the paper.

DISCUSSION BEFORE THE INSTITUTION, 28TH MARCH, 1940

Prof. R. O. Kapp: I should like to deal with the fundamental question of why we know now with so much assurance that transformer noise is due to magnetostriction. This was not by any means appreciated even in 1935, when a thorough search of world literature and the pooled knowledge of a most representative E.R.A. Committee brought to light only two papers on the causes of transformer noise, one published in the U.S.A. in 1931 and the other in this country in 1933; both these papers took it for granted that the cause was vibration of cores and stampings. It is true that it was appreciated at that time that magnetostriction must have some effect, and I saw an American patent specification which indicated such a suspicion; but the practical recommendations of these two papers and of a third which was published in 1936 were all based on what we now know to be the erroneous assumption that tightening-up core plates and similar mechanical work would reduce transformer noise substantially. Our present knowledge is primarily based on objective analysis of the sound.

Why should we be so sure that transformer noise is mainly due to magnetostriction and not to bodily movement of plates or coils? The presence of even harmonics is one of the clues, but Dr. Swaffield's work gave more solid evidence than that. He measured the magnetostriction curve of the iron used, and found that the whole change of dimensions was very small, of the order of a few hundred-thousandths of an inch in the case of a transformer of commercial size. He calculated the sound intensity that might be expected at a given distance from the transformer at each frequency if these very small changes in dimensions were the only cause, and found that the calculated value was of the same order as the observed value. The discrepancy which he noticed between the calculated and measured curves is not all due to experimental error. It is chiefly a measure of noises due to other causes, and proves that these are not negligible.

Another proof that the noise is mostly due to magnetostriction was obtained with two thin rings. Dr. Swaffield took two very thin coils, with which at 50 c./s. there was too little area to give an appreciable noise, and mounted them one at each end of a copper cylinder. The noise generated was found to be similar to that emitted by a complete core of stampings having the same dimensions.

Some 4 years ago Dr. Desch, of the National Physical Laboratory, suggested to me that there was probably such an effect as magnetostriction hysteresis, but this had never been proved, the reason being that there was no available technique. A point-by-point d.c. method was adopted by Dr. Swaffield, and the small displacements which are involved in magnetostriction were measured by means of a Lamb's extensometer, a very accurate but simple device which was manufactured at University College, London, for £15. Approximately a

movement of one ten-millionth of an inch, or 0·4 % of the total movement, could be measured. Fig. A shows the hysteresis loop plotted against H, and Fig. B shows it plotted against B to eliminate magnetic hysteresis. The slight lopsidedness also observable in Fig. 1 of the

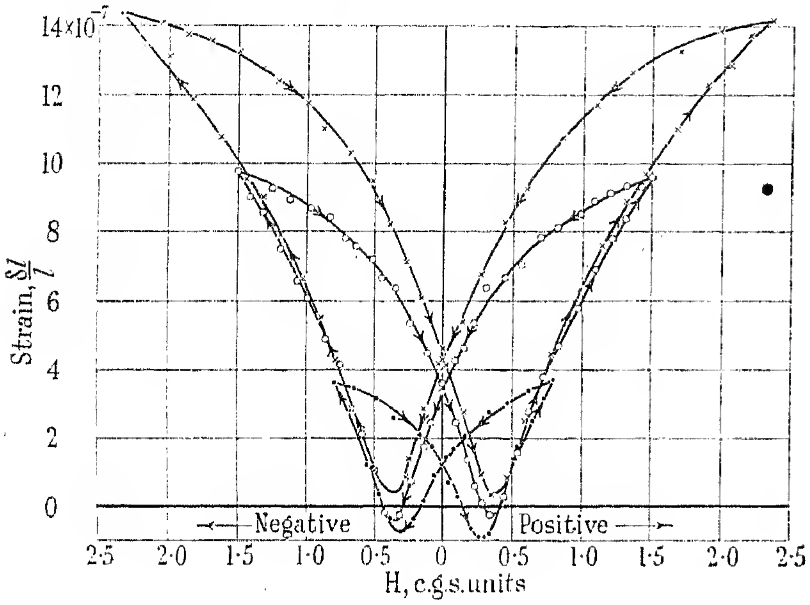


Fig. A

paper before us is, I think, not accidental. For it is also found on curves obtained by Mr. Alexander with a totally different technique. I cannot explain this lopsidedness. It may provide a clue to some fundamental property of magnetism.

Mr. C. W. Marshall: The study of transformer noise has gradually become intensified, largely because of the attitude of the public towards the growing practice of building transforming stations, particularly outdoor ones, in the vicinity of habitations. It may therefore be of

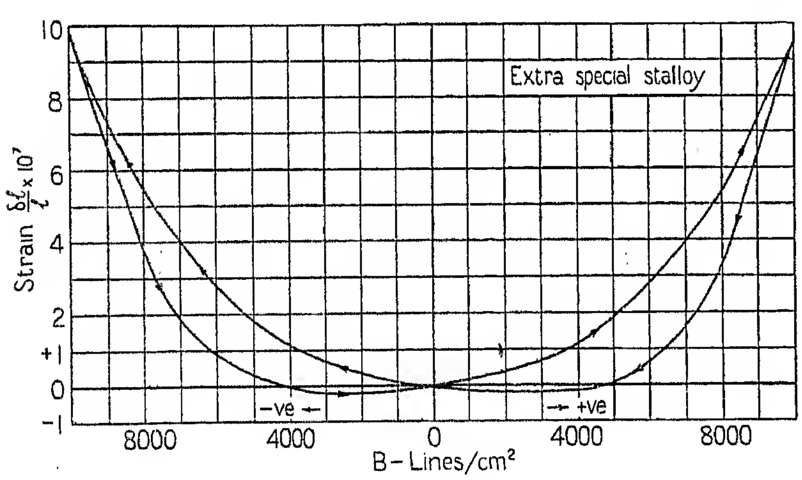


Fig. B

interest to give a brief account of some of the experience of this subject gained by the operation of the grid.

When the grid scheme was planned it was made a primary requirement that the operation of the transformers should be as silent as possible. Since that time 695 transformers, of an average capacity of 17 MVA each, have been in service for a period which may be expressed as about 5 000 transformer years. 15 complaints of noise have been registered, of which rather more than half have come from S.E. England—and mainly from districts near London—where only 34 % of the transformers are situated. This fact is in accordance with a generally accepted view that the effects of noise depend at least as much on the characteristics of the listeners as on the nature and intensity of the noise. Apart from such psychological difficulties there was the technical one, that no means of accurately measuring noise was available. Initially, improvised methods of measuring, or at least estimating, noise levels had to be used, e.g. the distance from a transformer at which the noise emanating from it became inaudible or the time required to mask the sound from a tuning fork by means of the noise from the transformer, were criteria by which the relative "noisiness" of similar transformers could be estimated. Such methods were unsatisfactory, and when Mr. Churcher produced a good subjective noise-meter it put an end to the use of improvisations such as those mentioned above. The subjective noise-meter has now given place to the objective instrument, which makes noise measurements as simple and convenient as light-intensity measurements. We are therefore in a satisfactory position for determining the noise output of any transformer.

In dealing with certain of the complaints mentioned above it was deemed necessary to take steps to reduce the noise emitted from certain of the transformers. The noise-reducing measures included lagging of transformer tanks, use of anti-vibration foundation pads, provision of stiffeners on tank surfaces, and substitution of natural cooling for forced cooling. While these modifications were effective, it has to be recognized that the expenditure involved is large compared with any benefit derived from the modifications. In my opinion, therefore, it is in the interests of both transformer manufacturers and users to get together and establish what are considered to be reasonable noise-levels for transformers of different types and capacities.

Mr. E. T. Norris: The authors devote a considerable portion of the paper to dealing with the masking effect of background upon the nuisance value of transformer noise. The theoretical methods of dealing with masking depend upon both noises being of exactly the same type, though in actual practice they very rarely are the same; and the human ear, fortunately or unfortunately, is extremely sensitive in discriminating between noises of different types. When a transformer is installed near a residence occupied by a placid, philosophic individual he will automatically in a short time reject the noise that is a nuisance and it will cease to trouble him; on the other hand, a nervy or highly-strung person is just as likely to go to the other extreme and select that noise and hear nothing else. Variations on that account, in my experience, almost obscure variations in the actual noise value (in phons) of the transformer. An interesting example of this effect is given in a recent paper on electric organs* where Messrs. Winch and Midgley stated that a noise—or, as they would call it, of course, a musical note—was unmistakably changed by the addition of a harmonic (i.e. another noise) which by itself was quite inaudible. These remarks may be summed up by saying that if a complete statistical analysis could be made of all transformers in service, both noisy and quiet ones, the correlation coefficient between noise and complaint would be found to be practically zero. This, of course, must not be taken to

* G. T. WINCH and A. M. MIDGLEY: "Electronic Musical Instruments and the Development of the Pipeless Organ," *Journal I.E.E.*, 1940, **87**, p. 517.

suggest that methods of noise reduction such as the authors describe are unnecessary.

The authors in some cases underrate previous efforts in the field of noise reduction. In particular, the work of the E.R.A. (to which Prof. Kapp has referred) in establishing that magnetostriction is not merely a cause but the principal cause of transformer noise, has been of great value to transformer designers and manufacturers in rendering unnecessary many attempts at improvement with which they might otherwise still be concerning themselves. The authors make arbitrary and incorrect assumptions regarding the method of noise reduction mentioned in Section (4)(*f*) and use these assumptions to deduce that the method is ineffective. The values given in the reference they quote, which were obtained by an independent authority, show a reduction from an average value of 86 phons (Fig. 2) to 69 phons, i.e. 17 phons, which is very nearly what the authors themselves claim as being reasonable commercially to-day. Yet this improvement was achieved in 1931,* and much better results are naturally possible to-day using the same principle.

I should like to ask whether the authors have yet applied their method of noise reduction to large transformer units. There would seem to be no limitation in this respect, but the paper refers to experiments on units of 60 and 400 kVA, and there are relatively few noise complaints in that range of size. I have been concerned with transformer design for a good many years, and I cannot recall a complaint relating to a transformer of less than 1 000 kVA, though there have been a few instances where noise complaints were anticipated and special precautions taken in the design and construction of the transformers.

Mr. N. Fleming: I propose to discuss solely the reduction of noise achieved by enclosing the transformer inside a building. A great deal of information is available from the work of the N.P.L. and other similar laboratories on the sound-reduction afforded by walls and partitions of various types of construction. In using such data to design sound-insulating enclosures, several factors have to be taken into account. As the paper emphasizes, alternative paths of low insulation must be avoided; a badly-fitting door, even though providing adequate insulation in itself, may seriously impair the overall insulation of the building. Ventilators, when required, may necessitate special acoustical treatment. In estimating the sound reduction to be expected from any given type of construction, it is, of course, necessary to take into account what the authors have termed the build-up effect. The magnitude of that effect can be calculated approximately on the ordinary reverberation theory, and where no special care is taken to provide sound absorption within the building the effect may be a loss of insulation of the order of 10 or 15 db. It is often desirable, therefore, to provide such sound absorption in the enclosure.

Another point which requires special consideration is the use of double partitions. These in general have a greater sound-insulation value than single partitions of the same weight, and so they may sometimes have advantages; but they have comparatively marked selective transmission, i.e. at certain frequencies they show very low sound insulation, and it may happen that such a low value may occur within the range of frequencies which are significant in transformer noise. For instance, a double window consisting of two sheets of 21-oz. glass, 1 in. apart, has an insulation value of about 30 db. at 500 c./s.; but at 200 c./s., where the minimum occurs, the sound insulation is only of the order of 10 db. If partitions of this nature are used, therefore, they should be properly designed in relation to the particular noise against which insulation is required.

Mr. A. G. Ellis: Much of the value of this paper lies in the fact that it is a record not merely of laboratory experiments but also of full-scale experiments. In such a problem, while laboratory experiments provide very good guidance as to the trend of development, definite conclusions applicable to practical designing can be satisfactorily drawn only from full-scale experiments. An example of this is to be found in Table 6. The tests on the small cemented ring core were very promising, but they were not substantiated by tests on actual cores of the types and sizes used in practice.

The information available now bears not only on the design of transformers but also on the design of installations, and it has been fairly well established that the design of the installation is at least as important as, if not more important than, the design of the transformer itself. As has been remarked, complaints of noise are relatively rare, and actual complaints may depend largely on the nature of the residential property and the tenants of the house. Speaking generally, I do not think that there is much demand for that perfect and uncommercial article, the silent transformer, although our efforts are still in the direction of providing it.

The question of establishing average noise-levels to which to work has been before us for a good many years, and I have always pleaded for time to collect sufficient data from experience. We are now arriving at the time when some such levels should be accepted for general working purposes. It is a difficult matter even at present to establish definite guarantees, because, as the authors point out, the results obtained on similar transformers built to the same drawings may vary by as much as 10 phons. If we do establish any form of acceptance-level guarantee, however, I think that we should avoid fixing figures involving a large tolerance. For example, a 15 % tolerance is apt to be regarded with disfavour by purchasers of electrical apparatus. What is really required to be established is a tolerable level of noise where quietness is of real importance, as in residential districts, transformer substations in office buildings and so on. For these cases a level of 40 phons seems to be generally acceptable; beyond that the noise may become a nuisance. An upper limit of, say, 90 phons might also be fixed, beyond which no transformer should be tolerated.

As regards the question of proving transformer noise to be due to magnetostriction, it is probably a good thing for the industry in general that this was not done earlier, because the result has been that transformer designers have had to investigate every possible source of noise. I do not think that there is much more that designers can do fundamentally until a better steel is produced, with very low magnetostriction; and the data available

* E. T. Norris: "Noise in Power Transformers," *Engineer*, 1933, **155**, p. 446.

in the paper and elsewhere on this matter are very scanty.

Referring to such an installation as is shown in Fig. 7, the level of the noise emitted by the radiators may still be higher than that required in quiet neighbourhoods, and in addition, if there is fan cooling, there is the noise of the fan. This latter has been avoided by substituting natural-draught chimney cooling for fan cooling; it is possible to avoid very high and rather unsightly chimneys by using the normal type of radiator.

The authors refer to the idea of burying the transformer underground. Burying a large transformer not only eliminates noise trouble but also makes the transformer proof against air-raid damage. The A.R.P. recommendations dealing with large outdoor transformers involve the building of walls round the transformers, and that will offset to some extent the cost of burying. The suggestion might well be examined further.

Mr. H. M. Lacey: I should like to endorse the remarks that Prof. Kapp has made as to the value of the work done by Dr. Swaffield. His work on the causes of transformer noise, and particularly the part played by magnetostriction, has established the matter on a quantitative basis. As an illustration of this, the curves of Fig. 2 of the paper are very illuminating. In Dr. Swaffield's formula for the sound pressure due to magnetostriction at a given point, the linear dimensions of the core occur to the third power. The kVA of a transformer is known to be proportional to the fourth power of the linear dimensions, and consequently the sound pressure should be proportional to the three-fourths power of the kVA. Thus if the outputs of two transformers differ in the ratio of 10 to 1, their outputs of noise should differ by 7·5 db. Reference to Fig. 2 shows that the three curves for 500, 5 000 and 50 000 kVA are, in fact, roughly parallel and separated by approximately 7·5 db. The fact that the curve for 50 kVA does not conform to this rule can be explained on the grounds that the linear dimensions would be less than the wavelengths of some of the components of the sound, and that consequently a transformer of this size would not be so efficient a radiator as those from 500 kVA upwards.

Reference has been made in the discussion to the necessity of collecting many data before reasonable noise-levels for various sizes of transformers can be established. The simple rule just stated should greatly simplify this work, because the establishment of a permissible noise-level for any one size of transformer automatically fixes the corresponding values for all other sizes.

The possibility of building a noiseless transformer by using core material having zero magnetostriction is interesting, although the suggestion is not new. Schulze* published data in 1927 showing that an alloy of nickel and iron having 81 % nickel had zero magnetostriction, and a year later the same author† showed that an alloy of silicon and iron having 4·45 % silicon had positive magnetostriction, whereas a similar alloy having 8·37 % silicon had negative magnetostriction. Thus, the possibility of manufacturing a silicon steel having zero magnetostriction is suggested. An interesting feature of such materials is that the composition which gives zero magnetostriction also gives minimum loss. This significant fact is important to transformer designers, since it implies that low iron loss would not have to be sacrificed should a material having zero magnetostriction and satisfactory mechanical properties be discovered.

Dr. E. Billig: I should like to confirm from my own experience most of the points the authors make, especially with regard to their practical results on transformers. In particular, our experience confirms that hardly any noise is generated by a transformer on short-circuit, even under full-load current conditions. All the noise originates in the core. Like the authors, we have found that clamping pressure has hardly any bearing on the amount of noise.

There are a few points in the paper which need explanation. Concerning the effect of silicon content on the magnetostriction, the authors show in Table 3 that 0·2 % silicon steel gives a magnetostriction value of 0·9 whereas 4·0 % silicon steel gives a figure of 1·3; but in Table 4 it is shown that under the same conditions the steel with the lower silicon content and the smaller magnetostriction gives a noise level of 39 phons as against 36 for the 4·0 % silicon steel. Mr. Lacey has referred to the interesting fact that the content of silicon which gives the least amount of magnetostriction at the same time gives the smallest loss. I rather doubt whether the use of such a high silicon content provides a practical solution; we know that the brittleness of the steel rises rapidly with the silicon content.

As regards Fig. 2, it would be interesting to know whether the tests were carried out on a complete transformer. It is unfortunate that the dimensions of the ring cores are not stated in Table 2.

Fig. 1 shows that the relation between magnetostriction and flux density is roughly parabolic. Magnetostriction could perhaps be explained in terms of an elastic deformation due to the magnetic strain set up in ferromagnetic materials. The magnetic pull is proportional to the square of the induction. Working out the amount of magnetostriction to be expected on these assumptions, one arrives at values approximately in accord with Fig. 1. From elementary principles, the longitudinal strain is given by

$$\alpha = \frac{B^2}{4\pi 10^3 \, . \, g \, . \, E}$$

where B = induction, in gauss; g = 981 cm. per sec. per sec.; E = modulus of elasticity = 2×10^6 kg. per cm^2, for steel. The lateral strain is $\beta = \alpha/m$, with m = Poisson's modulus = 3·44 for steel. Allowing for the compressibility (c), the lateral strain becomes

$$\beta = \left(c - \frac{1}{E}\right)\frac{B^2}{8\pi 10^3 \, . \, g}$$

Alterations of $\left(c - \frac{1}{E}\right)$ might be responsible for the peculiar shape of the magnetostriction curves shown by Prof. Kapp.

On page 542 the authors give some very interesting calculations of the amount of noise to be expected from a transformer of a certain size. For their example they assume an amplitude of vibration of 0·0001 in. With a

* *Archiv für Elektrotechnik*, 1927, **18**, p. 683.
† *Zeitschrift für Physik*, 1928, **50**, p. 448.

magnetostriction value of 1 in 10^6 for 10 000 gauss, the linear dimension must be 100 in. In the paper it is stated that most of the noise comes from the flat sides of the core and not from the corrugated ends. This is quite in agreement with our experience, but it means that to get a value of 70 phons the core stack in this example would have to be about 100 in. high, which is obviously wrong. It seems, therefore, that the amount of noise in a transformer cannot—even in order of magnitude—be explained by magnetostriction alone.

To investigate this point we have carried out some simple experiments on ring cores. They were magnetized to saturation and the amount of noise generated was measured by an objective noise-meter. We found that the noise from a complete ring core could hardly be heard. The rings were now cut radially, and little difference could be detected in the noise. Then a gap of $\frac{1}{16}$ in. was cut in the core, and again we could not hear much noise. Finally, the core plates were assembled with the gaps not lined up but with each alternate plate turned round through 180°, thus imitating an interleaved core of rather poor assembly. Here the noise started. This gave us the idea that a good deal of the noise emitted by a transformer must come from the joints, and that if mechanical movement of the plates in the gap is not stopped the core will tend to be rather noisy. The reason why we did not hear much noise when the gaps were all lined up is simply that the core was too rigid to follow the magnetic pull; but immediately the gaps are interleaved cross-fluxes pass from one plate to another and set up lateral movements giving higher noise-levels. This, too, shows the importance of building up cores from a small number of plates per packet only. The method the authors use for cementing their cores probably owes most of its success to the fact that it prevents movement of the type I have described.

The absorber shown in Fig. 3 consists essentially of a double-wall partition. From the theory of double partitions it is well known that it is essential to avoid bridging effects at the edges. It would seem that in the transformer design shown the partition is bridged above and below the absorber by the oil, thus transmitting the noise to the tank, unless perhaps the vibrations are propagated nearly in a straight line within the transformer tank.

Mr. J. S. Forrest: In investigating transformer noise from the point of view of the user, it was necessary for the Central Electricity Board to make a survey of the noise levels of a large number of existing transformers in order to determine what constituted the best of present practice. The next step was then to ensure that new transformers were at least as good as the best existing plant. For some years slow progress was made owing to lack of quantitative data, but in 1937 we developed a standard and convenient measuring technique making use of an objective noise-meter, and thereafter progress was more rapid. The meter was constructed in accordance with the American Standards Specification, and the procedure consisted of making a large number of measurements—say, 30 observations—round the transformer tank at a distance of 6 in. from the tank, the height of the observations being about 5 ft. above ground. The arithmetic mean of the readings so obtained was taken to be a measure of the noise emission and was termed the "average surface noise-level." After considerable experience with this method, we are satisfied that it is the best for general use, both on site and in the transformer shop.

The curves shown in Fig. C have been based on a large number of measurements made on site. Recently, measurements have been made on new transformers at the makers' works, and the results of some of these measurements are also shown in Fig. C. The figures given for the 10-MVA transformer are of interest. The higher reading was obtained when the transformer was operating on even taps, and the increase of 4 phons is due to the noise from the tap-changing reactors. It will also be noted that the 15-MVA transformer, which was Scott-connected, was unusually quiet. Both these transformers had passed the usual works inspection and tests without comment, and it was only the quantitative noise test which made these abnormalities apparent.

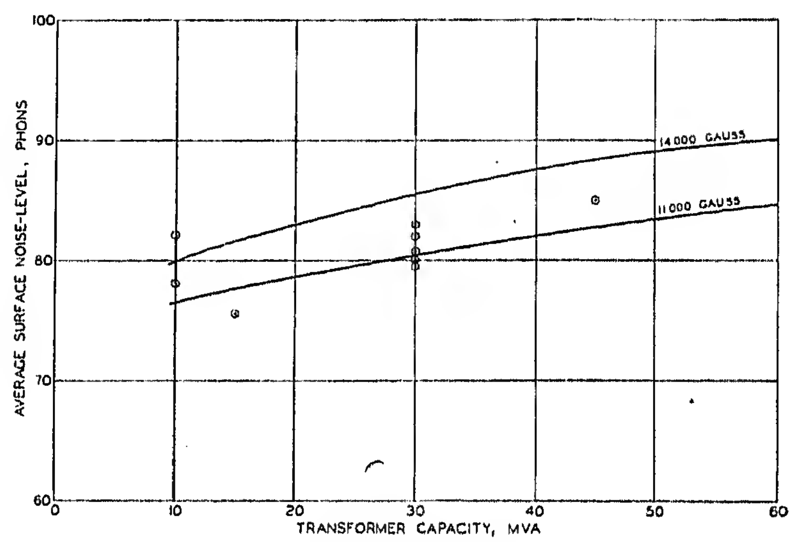


Fig. C

Tests made on site ——
Tests made at works ⊙

With regard to the test procedure, it is indicated on page 541 that the authors use a similar technique to that just mentioned, with the exception that their measurements are made at a distance of 1 m. from the tank surface. The exact distance at which these measurements are made is not of great importance, but it is desirable that some procedure should be standardized. We found it better to make the measurements as close as possible to the tank, in order to reduce the effect of background noise. In this connection, it is interesting to compare the curves given in Fig. 2 of the paper with those of Fig. C. The agreement between the two sets of results is moderately good, although the authors' figures, especially at low flux-densities, are higher than those given in Fig. C; the discrepancy may partly be accounted for by the difference in the method of measurement.

I am interested in the authors' work on internal absorbers, and, like Mr. Norris, I should like to have their views on the application of this method to large transformers.

As regards the variation of noise with distance from the transformer, the 6-phon rule given in Section 5(*b*) must be used with caution, as wide divergencies from the simple propagation law are commonly experienced. For example, in a particular case the noise at a distance of

40 yd. from the transformer was found to increase with the distance. In addition, a complaint has been received of noise due to a transforming station at a distance of $\frac{1}{2}$ mile; this complaint is not a frivolous one, and the noise on the complainant's premises seems to be intensified by stationary-wave and resonance effects.

Finally, although it is probably not practicable to specify a noise level for large transformers below which no complaints will occur, it would certainly be helpful to both manufacturer and user if accepted quantitative standards of noise emission were available, and I suggest that the time has now come when such standards can and should be specified for a range of transformer sizes and flux densities.

Mr. R. S. Dadson: I should like to ask the authors whether they could give some details as to how the figure of 40 phons, which they give in Section (2) as being the level at which complaints of transformer noise are liable to be made, has been arrived at. This question of the "dividing line" appears to me to be one on which further information is greatly needed, on account of the importance it would assume if it were proposed to accept noise measurements as a criterion of the annoyance values of transformers. A year or so ago I had the opportunity, in collaboration with Dr. Swaffield, of visiting transformer substations in connection with which complaints had occurred. I gained the impression that there was considerable variation in the extent of the complaints made, even in the case of substantially similar installations almost identically situated in relation to the residential property concerned.

It may be of interest to mention briefly some of the means adopted by the supply authorities to overcome the trouble. There were cases where comparatively simple screens, or soundproof covers, had successfully reduced the noise to a level sufficiently low to avoid complaints. Cases were also met where complaints had been made of the noise issuing from the transformer house through ventilating louvres, which had been successfully dealt with by covering the louvres with absorbent ducts containing numerous layers of absorbent material arranged parallel to the length of the duct.

The authors deal only with the core type of transformer, and do not give any details regarding the radial-shell type. In the course of the visits which I have just mentioned, it appeared that many transformers of the radial-shell type were unmistakably quieter than the core type of transformer of corresponding dimensions and performance. It would seem to be worth while to investigate the reason for this, and it would be interesting to see whether any light would be thrown on this aspect of the problem by the magnetostriction theory of transformer noise.

With regard to the calculations on the subject of barriers, I hope that Mr. Redfearn's work will be published as soon as possible. The point is of importance since the calculation of the screening due to barriers comparable in size to the wavelength of the sound involves the consideration of intricate diffraction effects which are often intractable by elementary methods. It is necessary to bear in mind, also, that screening effects may be profoundly modified by the presence of any other objects of appreciable size in the neighbourhood of the transformer, such as buildings, other transformers, fences and the like. In such cases it is unlikely that the effects of barriers could be calculated with any degree of accuracy.

Mr. W. Alexander: The curve in Fig. 1 appears to be almost identical with one obtained by Dr. Swaffield and myself in 1937, during a research on the magnetostrictive properties of transformer steel, which was carried out for the E.R.A. Dr. Swaffield was, at that time, investigating the question of noise in transformers, and my own interest was entirely in the magnetostrictive properties of the material tested. The method employed was that of Lamb's roller extensometer; it gave excellent results, but was found for certain reasons to be unsuitable for obtaining rapid measurements on a large number of samples. On account of these limitations I developed a method of measurement embodying an entirely different principle. A piezo-electric indicator was used for obtaining directly, oscillograms of the magnetostrictive movement on a basis of either flux density or magnetizing force. With the earlier method, information regarding "magnetostrictive hysteresis" was obtained only after a great deal of labour had been expended in determining many individual points. The latter method obviated such a laborious procedure.

The desirability of such an improved method is evident when it is considered that the obvious manner of overcoming noise due to magnetostriction is to develop a material which shows no magnetostrictive effect. In the process of development numerous samples would have to be tested. As is pointed out in the paper, certain iron alloys, namely nickel-iron (or Permalloy) and silicon-iron alloys, having various percentages of nickel or silicon, do show negligible magnetostriction, and according to the theory developed by McKeehan the magnetic property of high permeability at low values of magnetizing force is directly due to this "cancellation of magnetostriction." The figure of 6 % to 6·5 % of silicon in the alloy mentioned, is in fair agreement with the figure of 7 % obtained during tests by A. Schultz in 1928. The authors observed that the noise from the 6 % silicon-iron alloy was greater than that from the 4 % alloy, and this can only be due to the fact that the magnetostrictive properties of any sample of alloy depend, to a certain extent, on its previous magnetic and mechanical history, which might conceivably be very different from that of the samples used by previous investigators. It would be interesting to know whether the authors made any measurements to ascertain whether or not zero magnetostriction was approached in the sample actually used for the noise tests. It was due to the above factor that magnetostriction measurements were made on samples from the batch of stampings used by Dr. Swaffield for the noise measurements.

I would add that the concluding paragraph to Section (4) of the paper is rather unhappily worded. Until the effort has been made to find an alloy which has no magnetostriction, with suitable magnetic and mechanical properties, there is no possibility of eliminating noise due to magnetostriction in transformers. The presence of points of inversion from positive to negative magnetostriction as the percentage of nickel and silicon is changed in permalloy or stalloy shows the probability of this effect being common to many of the iron alloys, such

as iron-aluminium, iron-cobalt, etc. Since little is yet known of the magnetostrictive properties of these alloys, this leaves the field of investigation almost unlimited.

Mr. C. A. Mason: In the paper a figure of 40 phons is quoted as the maximum transformer noise level which can be tolerated outside residential property, and this is confirmed by my own experience of a figure in the region of 40 to 45 phons. In cases where complaints have been very severe we have made measurements inside premises and have found the noise level to be in the region of 30 phons. In general, I would suggest that conditions where the noise level due to transformers exceeds 15 phons inside premises where quiet conditions are required, such as in bedrooms, will form the source of a complaint. It is considered that the figure of 30 phons quoted by the authors is too high.

I note from Fig. 2 that a reduction of only 20 phons is obtained by reducing the flux density from 14 000 to 9 000. This agrees very well with my own experience of measurements which have been made over a range of flux densities on transformers ranging from 18 000 kVA downwards. It is evident that any large reduction of noise by this method is entirely uneconomic. In the case of large transformers, however, it is often an advantage to reduce the flux density, even if only by a small amount, in order to get a small reduction in noise, which, when combined with other methods, giving small reductions at the same time, will give a useful overall reduction.

I note from Table 7 that the authors have tried the effect of resiliently mounting the core and coils in the tank. I have carried out a number of similar tests on commercial transformers of ratings up to 500 kVA and have measured noise-reductions up to a maximum of 5 phons by this method. The reduction, however, was not general; in some cases no reduction at all was noticed. It would therefore appear that most of the vibration reaching the tank surface is transmitted by the oil and that only a small part is transmitted by direct contact between the core and tank. Tests have also been made in which resilient material was used to line the inside of the tank, the theory being that this might absorb vibrations in the oil and prevent them reaching the tank walls. No conclusive results were obtained, however, and these tests were abandoned as producing no useful noise reduction. I am also in agreement with the authors' conclusions regarding the lagging of the outside of the transformer tank with sound-absorbent or other materials in order to reduce the noise. It would appear that the energy in the vibrations reaching the tank is large and that any increase in the mass of the tank which is obtained by such lagging, even with concrete, is not sufficient to reduce the amplitude of these vibrations by any appreciable amount which would cause a useful reduction in the resulting noise.

In making noise measurements on transformers the effect of distance is of considerable importance. The authors' conclusions that the noise decreases by 6 phons each time the distance is doubled agrees with our own observations. In some cases the attenuation is a little greater than this, particularly with outdoor transformers which are situated in open country. In such cases the absorption due to the ground and such things as turf or small trees appears to exert considerable influence on the noise reduction. On the other hand, where a transformer is situated in a residential district, the reduction is often a little less than 6 phons owing to reflection from hard ground and surrounding property.

At this stage I should like to raise the question of standardizing the distances at which noise measurements should be made on transformers. I understand that it is the practice of some authorities to take measurements very close to the tank. Such measurements, however, often give results which are rather misleading when considering the amount of noise which is likely to be picked up at a distance from the transformer large in comparison with its dimensions. Accordingly, it would appear to be more useful to take measurements at distances from the transformer which are at least as great as the dimensions of the transformer, if not considerably greater. I should much appreciate the authors' opinion on this point.

I should like to emphasize the fact that when a transformer tank is coupled to an external cooling radiator by means of a pair of pipes, the noise appears to come entirely from the tank, that from the radiators being negligible. It also appears that flexible connecting pipes are not necessary. Using transformers of such a design, sound insulation boxes have been made and it has been found that reductions of the order of 20 to 25 phons are easily obtainable. The design of such boxes consists of an interior lining of sound-absorbent material such as Acousti-Celotex, the box itself being made of heavier material, usually some type of asbestos compound. The effect of brick enclosures on such transformers has also been investigated, and it appears to be possible to get a reduction of 42 phons using a single $4\frac{1}{2}$-in. brick-built enclosure. This reduction, however, is the measured reduction from the noise inside the brick chamber to that immediately outside. The particular brick chamber for which this figure is quoted was not lined on its inner surface with any sound-absorbing material, and accordingly the building-up effect which is mentioned in the paper was present. The amount by which the sound was increased inside the chamber by this effect was of the order of 10 phons in this particular case. Accordingly, the net effect of the enclosure would be to reduce the transformer noise from that which would be experienced when the transformer is operating under free-space conditions by about 30 phons only; with a reduction of this order, however, it was still impossible to detect any noise whatever from the cooling radiators, which were mounted outside the brick chamber and connected to the tank by rigid pipes. The question of the amount of sound contributed by vibration in the radiators has always been doubtful, but from theoretical considerations it would appear that in view of the small dimensions of the cooling radiators they could not transmit sound of the long wavelength which is in question except with the poorest efficiency. In my opinion the sound contributed by the radiators can be ignored even when the radiators are bolted directly to the tank. I should like to have the authors' opinion on this point.

These views are supported by a number of tests which have been carried out on cooling pipes on transformer tanks; in many cases where cooling pipes have been noticed to be vibrating, steps have been taken to prevent

such vibration entirely by suitable clamping, but there has been no appreciable change in the resulting noise level from the transformer unit.

Mention has been made of the probable sound-insulating effect of kiosks which are used to house small distribution transformers. Tests have been made on such kiosks housing transformers of ratings from 100 to 600 kVA. The measured reduction in noise level from that inside the kiosk to that immediately outside varied from 5 to 18 phons according to the position outside the kiosk at which the measurement was made. The least reduction is naturally obtained near the ventilating louvres, and the greatest near those parts of the kiosk where there are no openings. The whole question of the amount of sound insulation present in a kiosk appears to be almost entirely a function of the number and position of openings in the kiosk, and not of the thickness of the material from which the kiosk is made. The average reduction in noise due to a kiosk, obtained from measurements made at a considerable distance from a kiosk, amounts to about 10 phons. In view of the fact that enclosing a transformer in a kiosk will probably result in a small increase of noise level, it is reasonable to assume that the resultant effect of a kiosk in reducing the noise is not very great.

Whereas in the past it has often been assumed that transformer noise is due to the presence of a loose core, it appears that tests which the authors have made agree with my own conclusion that clamping of the core is not of major importance. I would take this opportunity, however, of emphasizing that this conclusion applies only to oil-immersed transformers. So far as air-cooled transformers are concerned, clamping and cementing of cores appears to have far more effect. One particular test which I witnessed is interesting as illustrating this point. A small 50-kVA 3-leg transformer core was taken in which the outer punchings of the middle leg were unclamped and were very loose. When the transformer was excited in air, these loose punchings caused a rattling noise of such a magnitude that it completely masked the normal low-pitch transformer hum. With the excitation still on, this core was lowered into a tank of oil. As soon as the loose punchings were covered with oil the rattling noise disappeared entirely, and the only noise which could be heard was the usual low-pitch hum. Such a test as this illustrates the futility of attempting to explain transformer noise on the sole assumption that the core is not sufficiently clamped.

Dr. J. Swaffield (*communicated*): I am very interested in the curve (Fig. 1) representing the relation between magnetostrictive strain ($\delta l/l$) and flux density, and in the authors' deductions from it. It would be interesting to know the method of measurement and the exact form of the specimen on which the curve was obtained. As Prof. Kapp has pointed out, this curve is practically identical with one which we obtained in our transformer-noise work for the E.R.A.; this was plotted from measurements on an annular specimen, with no air-gap, and the silicon content of the steel was 4·4 %. The interesting feature of these hysteresis loops on a flux-density basis is that they are traversed in the opposite direction to that normally associated with magnetization cycles. So far as the flux is concerned it would be more correct, therefore, to refer to the effect as a "time-lead" rather than as a time-lag.

Apart from the effect of hysteresis, which in fact only introduces a comparatively small change in the wave form of the core surface movement, the authors suggest that, since $\delta l/l$ is not proportional to B, the variation in extension during a cycle is not sinusoidal. This suggestion is incorrect, as it does not take account of the frequency-doubling action of magnetostriction; it is easy to show that the relationship of $\delta l/l$ to B required to produce a pure sine-wave motion of the core surface is not linear but parabolic.

The phrase "magnetostrictive forces" which is used in the paper is apt to be misleading. Magnetostriction is primarily a matter of strain, not of stress; the curve of magnetostrictive strain is not associated essentially with any forces and, if the flux cycle is traversed sufficiently slowly, the cycle of movement takes place without any forces being induced in the core. At frequencies high enough to be appreciable compared with the mechanical resonant frequency of the core, the actual instantaneous strain lags behind the magnetostrictive strain owing to the inertia of the core. The alternating driving force needed to maintain the core mass in vibration is that associated with the mechanical strain (and hence stress) which is the difference between the magnetostrictive and the actual strains. Furthermore, the amplitude of the actual strain is now greater than that of the magnetostrictive strain; in other words, the core movements are now greater than those which would be deduced for the static conditions. For mechanical conditions such as would be associated with the main resonance in a simple transformer core, at a frequency of f cycles per sec. the relation

$$\frac{\text{Amplitude of actual strain}}{\text{Amplitude of magnetostriction strain}} = \frac{1}{1 - (f/f_0)^2}$$

holds for values of f well removed from the resonance frequency f_0. Thus, in general, the core vibration amplitude is not limited to that given by the magnetostriction curve, even at frequencies remote from the resonance. The main resonance of the core is quite likely to be as low as 1 000 c./s., or even lower, in a large transformer.

I am sorry that there is nowhere in the paper a table of the E.L. values of the various component frequencies taken from an actual transformer. The analysis shown in Table 2 (which refers to a single ring lamination) is not necessarily of much significance since it is the edge of this single lamination which corresponds to the core surface of an actual transformer (so far as magnetostriction effects are concerned), and it is absurd to suppose that any radiation takes place from the edges. The noise in this case must surely be due to the very small compound alternating stresses set up causing vibration of the lamination, in the direction at right angles to its plane, in many modes simultaneously.

Nevertheless, it seems clear that the middle harmonics (say, 300–800 c./s.) in a normal transformer may be expected to be responsible for a very large proportion of the total noise. Referring now to Table 3, I should like to emphasize the need for considering magnetostriction curves as a whole and not merely values of strain at

isolated flux-densities. To take an extreme case, suppose that the magnetostriction curve were exactly parabolic in shape. All components other than the fundamental would then be suppressed as explained above, and the loudness of the noise due to magnetostriction would become a minute fraction of that found in practical cases for the same maximum strain. In this respect, if a steel could be produced having a parabolic magnetostriction curve, it might go a long way towards solving the problem of the generation of noise. Incidentally, it is not clear why the value of $\delta l/l$ for 4 % silicon steel at $B_{max} = 10\,000$ (given as $1 \cdot 3 \times 10^{-6}$ in Table 3) is different from the value given for the same density in Fig. 1 ($1 \cdot 0 \times 10^{-6}$).

The authors' conclusions on the subject of noise emanating from the core joints confirm those which we reached. In particular, the application of very large clamping forces will do little or nothing to eliminate noise from a joint which, owing to bad interleaving, is inherently noisy.

Prof. Kapp's suggestion about the asymmetry of the magnetostriction curve is only one of the large number of interesting points which arise in considering the fundamental relationships between transformer noise and the properties of the iron. It will be a great pity if investigation of these basic effects is not pursued further simply because no hope can be seen at present of eliminating the trouble by such means. A report dealing with the fundamental transformer noise work which we did for the E.R.A. at University College, London, and which I have referred to above, will be published shortly.

[The authors' reply to this discussion will be found on page 564.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 8TH APRIL, 1940

Mr. E. C. Rippon: The problem of limiting noise is really a legal rather than an engineering one, since the noise level which constitutes a nuisance has not yet been defined by a legal decision. In other words, no quantitative standard is available on which to base the noise level of installations.

There are two methods of attacking the problem from the legal aspect. First, the transformer may be silenced by the use of special designs incorporating elaborate soundproofed chambers. It is doubtful whether this ideal can be attained economically in practice. Secondly, the transformer installation should embody, where applicable, all the known noise-abatement measures, so that if legal proceedings are initiated it can be said that every step has been taken to reduce the nuisance to a minimum. It would appear that this course is the only one open to supply undertakings at the present time.

Apparently several cases regarding nuisance caused by noise have been tried in the law courts, but no legal decision on the noise level which constitutes a nuisance has yet been given. If the authors have any knowledge of a legal precedent, even where the case has been dismissed, it would be of considerable interest and value to the industry if they would give details, with particular reference to the noise level of the installations concerned.

The authors suggest from their experience that in residential districts the noise level immediately outside a house should not exceed 40 phons. This will correspond to 30–35 phons within a room in the house with the windows open. Whilst the problem is bound up with the psychological aspect, it can be said that the noise level mentioned by the authors is approximately the level obtained on satisfactory installations, although in my experience at least one serious complaint has been made about a noise level of not more than 30 phons. Since the legal and psychological aspects still depend on individual opinions of the plaintiff and the court, a minimum figure such as 40 phons can only be regarded as a rough guide to practice; special conditions, usually subjective, may exist which can only be satisfied by a lower noise-level.

Referring to the construction of transformers to reduce noise omission, the authors state that practically no improvement is obtained by using excessive clamping pressures. This is generally agreed and borne out by tests on actual transformers by various manufacturers. It should be stressed, however, that the design of the transformer clamping frames is of some importance, and although, fundamentally, a large proportion of the noise emitted by the core is due to magnetostriction, the vibration of the unsupported edges of the yokes and the vibration of the interleaved joints can considerably increase the noise level. It is at these points that the clamping frames should exert a uniform pressure. Experimental data relating to cemented cores confirms the authors' opinion that no appreciable reduction in noise emission is obtained by using this method on 3-phase commercial transformers.

In Section (4)(*d*) the authors discuss the effect of flux density upon the noise level of transformers. I agree that to effect a substantial reduction in the noise level by reducing the flux density is quite impracticable if the attempt is based on the information given in Fig. 2. The noise-level values shown in this figure are higher than those obtaining in normal practice for commercial transformers. By suitable design, with due regard to the mechanical construction, transformers have been produced operating at flux densities about 20 % below normal, with satisfactory results both from the noise-level and from the economic aspects. The mechanical construction of the transformer and its tank, in relation to the natural frequencies of its component parts, is an important factor when reductions in the equivalent loudness of the transformer noise are being considered. Modifications to tank stiffeners make little contribution to the reduction, but considerable improvement may be effected by special tube and under-base design. As an example of this I would mention some large transformers of tubular tank construction which were installed in the same substation as certain other transformers, operating from the same supply and at the same flux density. One type had a noise level about 30 % higher than the other. The noise levels were recorded on the same instrument under identical background and load conditions. It is obvious that the reduction in the equivalent loudness of the noise emitted was due to the better design of the clamping frames, cooling tubes and under-base. Prob-

ably the most marked effect of sound mechanical construction makes itself apparent when two similar designs are compared having approximately the same equivalent loudness, but where one design can be readily distinguished by some high-pitched sound, presumably owing to overtone resonance in some part of the structure; in other words, where one transformer has a higher "nuisance value."

Resilient barriers or absorbers, interposed between the transformer windings and the tank sides, appear to have a limited application, owing to increased dimensions of the tank, particularly on the larger units where rail-gauge limitations dictate the design proportions of the transformers. On smaller transformers up to, say, 1 000 kVA to 2 000 kVA, noise complaints are not common: first because the transformers, owing to their size, have a lower inherent noise-level than the larger units; and secondly, because they are usually installed—apart from the outdoor pole-mounting type—in some form of building. The authors have carried out extensive tests on their proposed absorbers which are made of cellulose sheets; it would be of interest to know whether they have carried out any tests to demonstrate that the fire risk is not increased by such barriers.

Mr. R. S. Orchard: It would be interesting to have any information the author can give on the comparative noise-levels of transformers with interleaved and butt-type joints.

On page 549 he states that it is not as a rule necessary to fit external resilient supports, but I should like to draw attention to the importance of careful design of these supports when fitted. Where tap-changing equipment is installed the centre of gravity of the transformer is frequently off the centre line, and unless special care is taken in the design of such supports tilting of the transformer may result. This, apart from being a bad mechanical arrangement and giving a poor appearance, also gives rise to difficulty in obtaining the correct mounting of Buchholz relays.

The paper emphasizes the progress which is now being made in regard to the limitation of transformer noise, and it would seem that it will soon be possible to specify definite noise-levels which should not be exceeded by a transformer of good design. It is to be hoped that the manufacturers will endeavour to set up suitable standards shortly.

In Tables 3 and 4 the authors gives figures relating to the magnetostriction effect associated with different grades of sheet steel. It would be of interest if he could add to these Tables the comparative figures for the low-loss iron which is used extensively on the Continent and in America for transformer cores. I understand that the losses in this iron are of the order of 20 % less than in the iron normally used by British manufacturers.

Mr. C. Turnbull: The paper states that noise is something which is undesired by the recipient; but sometimes the recipient desires to hear noise so that he may take the case to the law courts and receive damages for alleged disturbance. Anything that can be done to reduce the noise due to transformers will be a valuable asset to the industry, as large substations have now to be placed in residential districts.

Would the noise be reduced by putting the transformers in corrugated tanks? Such tanks would appear to be less likely to reverberate than those normally used.

Mr. R. W. Mann: In the physical experiment carried out by the author with a metal tank and a cotton-wool tank, when one side of either tank was slightly lifted from the floor the noise-cushioning effects of the two tanks were approximately equal. This would seem to suggest that the noise-reducing effect of the enclosure depends considerably more upon its airtightness than upon the actual thickness of the material. That is, if the cotton-wool tank were compressed so as to make it as airtight as the steel tank, then the noise-reducing effects might well prove to be more or less equal.

Mr. K. W. McBain: Prior to the reading of this paper other investigators had arrived independently at conclusions similar to those mentioned by the authors, namely: (1) The ineffectiveness of additional clamping pressure on cores as a means of obtaining any reduction in noise level. (2) A noise reduction, on larger sizes of transformers, of 10 to 15 phons for a reduction in core density from 13 000 to 10 000 lines per cm². (3) A reduction of 5 phons due to the resilient mounting of a transformer inside a substation. (4) A reduction of 40 phons for indoor substation transformers using an external radiator arrangement like that shown in **Fig. 7,** and using brick walls 9 in. thick for the substation.

If the site situation were such that it was found necessary to build a specially designed substation for quiet operation (e.g. a basement substation), a further reduction of approximately 20 phons could be obtained.

Since the design of the substation is a contributory factor, some operating engineers make the provisions necessary so as to reduce the transformer noise-level to a practicable commercial standard. Unfortunately, some other operating engineers do not give the question of transformer noise sufficient attention in the early stages of their projected schemes. In many instances the transformers are installed in most unsuitable sites, and upon the receipt of the first complaint from adjacent residents the operating engineer calls in the manufacturer and bitterly complains of the noise due to the transformer, even though the noise level may not be above "normal."

It is to be regretted that the paper does not consider typical examples of substation sites, giving the measured noise-levels at such sites both inside and outside the substation, as well as at various distances at which dwelling houses are located. The following are some of the results obtained from three different types of substations.

Installation No. 1.—This is a substation of conventional design containing a 500-kVA tubular-tank transformer operating at normal full load with a core density of 13 200 lines per cm². The walls of the substation are 9 in. thick, the doors 2 in. thick, and ventilation is by louvre openings in the doors. The noise level inside the substation is 72 phons. The noise level immediately outside the door of the substation is 39 phons, thus giving a reduction in noise level of 33 phons. The noise level measured 25 ft. from the substation is 26 phons.

Installation No. 2.—This is a substation specially built for quiet operation and containing a 500-kVA transformer with a separately mounted radiator, as shown in Fig. 7. At normal full load the transformer operates

with a flux density of 13 200 lines per cm². The substation consists of a 9-in. thick brick building having 2-in. thick doors without louvre openings. The transformer is mounted on a resilient material. The following noise levels were recorded: inside substation, 69 phons; immediately outside door of substation, 28 phons (giving a reduction in noise level of 41 phons); adjacent to the radiators, 24 phons; at a distance of 15 ft. from the substation, 21 phons. The average noise-level 30 ft. distant from the substation was 10 to 15 phons.

Installation No. 3.—This is a substation located in the basement of a block of flats and specially designed for quiet operation. The substation contains a standard 500-kVA transformer with cooling tubes around the tank and operating at approximately 13 200 lines per cm². The transformer is enclosed in a separate enclosure using 9-in. thick walls and 2-in. thick doors. The ceiling of the chamber is 3 in. thick and is lined with paxfelt 1 in. thick. The ceiling of the basement is 15 in. above the ceiling of the transformer chamber, and ventilation to the transformer enclosure is provided by suitably lined ducts. The following results were obtained: noise level inside transformer chamber, 66·5 phons; average noise level in basement adjoining transformer chamber, 32 phons (giving a reduction in noise level of 34·5 phons). The noise level in the ground floor of the flat directly above the transformer chamber was less than the background level (10 to 15 phons).

Other installations in similar locations to Installation No. 3 where no precautions whatsoever had been taken in the layout of the substation, gave noise levels in the flat directly above the substation of 30 to 35 phons.

From these examples it will be noted that the transformer with a separate externally mounted radiator gave the best reduction in noise level between the inside and outside of the transformer chambers. I would mention that in a number of installations employing a separately enclosed transformer and external radiators, no sound from the radiators themselves could be detected: this is contrary to the views put forward by the authors.

I consider the flexible pipe connection shown in Fig. 7 unnecessary; if a piece of steel pipe were substituted it would not make any difference to the results obtained.

The results from Installation No. 3 indicate the advantage of using a ventilated enclosure within the transformer substation. The very fact of using a separate enclosure combined with the sound-insulating properties of the basement ceiling is sufficient to reduce the noise level in the first floor of the flat to below the complaint level.

I should like to mention a large transformer substation where two 18 000-kVA specially designed outdoor-type transformers were successfully installed and have been in operation for some years. The substation is now surrounded by residential property. The transformers were resiliently mounted in a shallow grass-lined pit. The measured noise-level is 56 phons within a distance of 6 ft. from the tank, as compared with 75 phons for an average installation of this rating. The nearest house is only 100 ft. distant from the transformers, and while at this distance the noise level due to a standard transformer would be approximately 51 phons the measured noise level of these transformers is only 32 phons, which is below the complaint level. Trees and shrubs have been planted around the site; these not only provide additional sound absorption but also considerably improve the appearance of the site.

Mr. W. L. Kidd: On page 553 the authors point out that where it is necessary to limit the noise of air-blast-cooled transformers, attention has to be given not only to the transformer noise but also to any noise that may arise from the fans or air jets. I should be glad if they would give some further information in this connection. Until recently the noise emitted by certain fans or air jets, and occasionally even by pumps, had been as great as the noise emitted from the transformer itself, and a considerable amount of work has been carried out by many manufacturers in order to reduce the noise level from the cooling plant to a minimum. Experience shows that a general reduction in the speed of fan motors has taken place, but even this is in many cases not considered sufficient to meet the requirements of built-up areas, where a more expensive type of cooling which avoids the use of fans has been adopted.

I think it worth while to emphasize this point because manufacturers do not in certain instances give it sufficient attention. For instance, in my own experience there was the recent case of a large 132-kV transformer which had to be held for some time in the works for improvements to be made to the fan arrangements because the first installation of this type had proved too noisy on test.

THE AUTHORS' REPLY TO THE DISCUSSIONS

Messrs. B. G. Churcher and **A. J. King** (*in reply*): As stated at its presentation, the paper was written with the object of its being of interest and assistance to power system and consulting engineers and transformer designers in considering transformer-noise limitation. Accordingly the space devoted to the magnetostriction aspect, which has so far led to no practical solution, was limited to two pages. It was felt that a detailed discussion of this matter, and of others investigated by us which are not even mentioned, would have been out of place. However, as the contribution of Prof. Kapp to the discussion is confined to the magnetostriction aspect and as it might possibly create misapprehension as to the origin of the matter of Section (3), it has become necessary to make the position clear.

In the first place it is important to keep in mind the distinction between the study of magnetostriction as such or as a fundamental cause of transformer noise, to which Prof. Kapp and his associates have contributed, and the general problem of transformer-noise limitation with which this paper deals. Transformer-noise limitation is essentially an engineering problem. It is usually recognized that such problems require for their effective treatment the consideration of all relevant factors as well as basic principles and the appraisal of alternative solutions in the light of these considerations. In this way a sense of proportion is maintained and, in the present problem, the elimination of magnetostriction is seen to be not a *sine qua non* but simply one of several possible measures. The most valuable solution is that which achieves the

desired result in the most economical and convenient way. It may be, but is not necessarily, one indicated by a consideration of basic principles alone. It is possible to build small noiseless transformers at the present time by using low-magnetostriction core material, but the method is far from being either economical or convenient. That solution is, as we say, not at present practicable. Its practicability is conditional upon the development of materials which not only embody negligible magnetostriction but are also adequate in respect of energy loss, permeability, mechanical properties and, moreover, cost—a problem which should not be underestimated. No special knowledge is required to reach this obvious but nevertheless important conclusion. It should also be appreciated that the problem of noise arises with only a small proportion of all the transformers made. The use of measures applicable to a transformer of standard design rather than those requiring a special design (as would probably be the case with special core material) is therefore an important advantage to both user and manufacturer. Consideration of the subject of the present paper exclusively in terms of magnetostriction may even lead to misapprehension as to the real issue. This seems indicated in the last paragraph of Mr. Alexander's contribution. Transformer noise is not something occurring "in" the transformer but is the undesired aural sensation experienced by a hearer due to the transformer, and that is what needs elimination. Methods of effecting this are described in the paper. Apart from the fact that efforts have been made to find an alloy which has no magnetostriction combined with suitable mechanical properties, both the statement that "there is no possibility of eliminating noise due to magnetostriction in transformers," and the impression it gives that the whole problem turns on magnetostriction, are misleading.

Prof. Kapp's remarks might lead those unfamiliar with magnetostriction to conclude that it is an obscure phenomenon, the measurement of which has been only recently achieved. On the contrary, magnetostriction in iron and its non-linear relation to magnetization has been known, and measured, for nearly a century. J. P. Joule* and Shelford Bidwell† were early investigators. Many others followed with improved technique and by 1931 the existence of magnetostriction hysteresis was fully established.‡ It is therefore difficult to understand Prof. Kapp's statement that the existence of this phenomenon was not proved in 1936.

Consideration of transformer-noise test data which we obtained at various times from 1930 onwards led to a systematic investigation being started in 1934. As one of the probable causes of noise, magnetostriction was investigated, measurements on strip specimens of transformer and other steels being made in August of that year. The magnitude and non-linear character of the effect observed by others was confirmed. The harmonic character of the sound spectrum which had been observed on transformers was seen to be consistent with the observed extension. By an approximate calculation for a typical case, it was found that the magnitude of the fundamental tone (100 c./s.) was not inconsistent with the extension which had been observed for transformer steel.

* *Philosophical Magazine*, 1847.
† *Proceedings of the Royal Society*, 1884, 5, **38**, p. 265.
‡ W. ALEXANDER and J. SWAFFIELD: *Beama Journal*, 1937, **41**, p. 99.

Experiments were also carried out between April, 1934, and July, 1935, with a.c. magnetization on cores of the simplest possible form, in order to minimize or eliminate other causes of noise. Jointless ring cores and a rigid cage winding were used. (A slide was shown at the meeting.) Experiments were carried out which showed that any contributions to the noise from winding vibration, non-uniformity of magnetization, magnetic non-uniformity of the core (e.g. effect of assembly of punchings with respect to rolling direction) and eddy currents in the core were negligible. These experiments showed that magnetostriction, which had been proved to be present in the material of which the core was made, was the sole remaining primary cause of the noise observed. In this case also, for a core of 2 in. axial length, the magnitude of the fundamental component of the radiated pressure was found to be not inconsistent with the primary cause being magnetostriction, assuming simple radial expansion of the core. It was found, however, that this assumption was not tenable for a single ring punching. Although the area of the outer edge was very small compared with that of the above core, the noise level for given flux density was little less. The same type of harmonic sound spectrum was present but the noise was radiated in an axial direction rather than radially (page 544) and the mode of vibration was quite obviously not one of simple expansion. A possible explanation of this axial vibration is the radial variation in flux density in the ring, causing an umbrella type of vibration due to the magnetostriction strain being greater at the inner than at the outer radius. Whatever the precise mechanism of vibration, it could not be gainsaid that magnetostriction, known to be acting, was the primary cause of the vibration, since there was nothing else to account for it.

Another important factor determining the vibration of a core, which should not be overlooked, is the mechanical constraint imposed by the form of construction used (mentioned on page 542). This was illustrated by the effect of slightly bending the single ring punching by the fingers while under a.c. magnetization. The predominant pitch of the sound rose and, by different degrees of constraint, the pitch could be caused to traverse the musical scale. The sharpness of the tuning indicated that while magnetostriction was the primary cause of the vibration, the harmonic vibrations were accentuated in turn by the changing mechanical resonance. A further and conclusive demonstration of the effect of mechanical constraint was afforded by tests on a jointless ring core of ½ in. axial length made in July, 1935. In the first test the core was tightly bound all round with strong tape. Under a.c. magnetization the noise emitted was largely axial. The core was then cemented into a solid mass. At a given flux density the reduction in noise due to cementing was over 25 phons. Analysis showed that all the components were reduced in amplitude and many entirely suppressed. Thus without altering the magnetostriction conditions a substantial change in noise had been effected by imposing very complete constraint on the axial movement of the laminations, the movement evidently having been largely in this direction. In addition to radial variation in flux density, such a mode of vibration might be due to differences in flux density

or magnetostriction coefficient between adjacent laminae. By selecting a form of core favourable to the simple expansion mode of vibration, such as a well clamped and cemented ring core of fair axial length, it may well be that a simple correlation between the shape of the magnetostriction curve and the radiated tone structure can be shown. On the other hand, a very short core vibrates by a different mechanism, such as that of differential magnetostriction. In a core of normal proportions both modes of vibration would be present and their relative importance would depend on a number of factors, including mechanical constraint to different modes of vibration. Hence, for a normal transformer core the relation between the magnetostrictive properties of the steel and the noise radiated is far more complex than that associated with the type of core experimented with by Dr. Swaffield. We note that Prof. Kapp disagrees with Dr. Swaffield's view that the discrepancies between calculated and measured sound intensities on a long ring core are well within the probable limits of error in calculation. Prof. Kapp envisages other causes of noise but does not suggest what they are. Our own work leads us to conclude that while magnetostriction is the primary cause of noise in a jointless core, several factors (not other causes) mentioned above determine the quantitative relation between the magnetostrictive properties of the steel and the noise radiated by a core of given construction.

It had been clear to us from the outset that the possibility of limiting transformer noise by using core materials of low magnetostriction would depend upon whether such materials, if commercially available, met all the other rather exacting requirements in respect of energy loss, permeability, mechanical properties and cost. None of the three commercial grades of steel tested showed any material superiority in regard to magnetostriction. Permalloy and 6 % silicon steel, both having low magnetostriction effects, were dismissed for reasons stated in the paper. Having satisfied ourselves that magnetostriction was the primary cause of transformer noise and that existing core materials that were practicable from other considerations showed no advantage in respect of magnetostriction, we decided that, from the standpoint of immediate future policy, there was no object in pursuing the magnetostriction aspect further, and by July, 1935, we had turned our attention to other methods. As far as we are aware, no practicable low-magnetostriction material is yet available but, as pointed out in the paper, such a material may be available in the future.

Mr. Marshall's remarks on experience of transformer noise on the grid system are of great interest. We note his comments on the psychological aspect of noise, to which we refer in Section (2) of the paper. Even if a completely satisfactory criterion of noise were found (i.e. one more satisfactory than loudness) and a consistent, universal system of measurement established in terms of it, with accurate objective meters for practical measurement, there would always be individual differences of opinion as to what noise magnitude is tolerable, in the same way that there are differences of opinion as to what room temperature is tolerable. As long as the present loudness basis continues to be accepted, the development of objective meters capable of measuring noise in general in phons (a problem by no means completely solved) is of great importance. A contribution to this end will shortly be published. Mr. Marshall also draws attention to the desirability of establishing what are considered to be reasonable noise levels for transformers of different types and capacities. This would be a useful step but it would need to be preceded by the adoption of objective meters indicating in accordance with the British Standard of Equivalent Loudness, alluded to above. As a result of many years of engineering development, the design of power transformers has crystallized out along fairly well defined lines, which inevitably result in the emission of noise of the order of 70 to 85 phons near the transformer. Where a materially lower level is essential it may be a question of balancing the cost of locating the transformer at a greater distance from potential complainants against that of employing other measures, such as those discussed in the paper. In either case additional cost inevitably and justifiably arises. To ensure effective and economic results, collaboration between manufacturer and user is desirable, not merely as to general standards but also in the planning stage of particular installations. Hence, although agreement as to what may be considered reasonable noise levels for transformers of different types and outputs, and for different locations, would help to clarify the position, it would not of itself provide a general solution, because the conditions of particular installations vary over a much wider range than the noise levels of commercial transformers of a given type and capacity.

Regarding Mr. Norris's remarks on methods of noise reduction by tank construction discussed in Section 4(*f*), we are unable to trace the arbitrary and incorrect assumptions attributed to us. In the recent article by an independent investigator referred to* the noise levels with the double-sided construction (20 000 kVA) and with lagging (30 000 kVA) respectively are given, but the levels without these measures are not given. Without knowing the respective flux densities at which these transformers operate, which are not given, it is not possible to deduce the noise reductions from the curves to which the reader is referred. We therefore accepted the author's conclusion, viz. that "in both cases a reduction in average surface noise level of about 10 phons had been effected." We are interested to note the figure of 86 phons, which Mr. Norris now gives for the 30 000-kVA transformer before lagging, corresponding to the 17 phons reduction claimed. We take it that this result is due to a layer of lagging only and not in part to an external casing. Measurements by us at 300 c./s. with a cotton-waste enclosure, out of contact with the source so as to produce the maximum attenuation, gave a reduction of approximately 1 phon for a thickness of $1\frac{3}{4}$ in., compared with 26 phons for a $\frac{1}{8}$ in. thick steel enclosure. This was demonstrated at the meeting and supports our contention that an inconveniently large amount of lagging is required for a reduction of 20 or even 17 phons. We agree with Mr. Norris that there is no known reason why the absorber method should not be applicable to larger transformers. Owing to the pressure of more urgent work we have not had an opportunity of extending the method beyond 400 kVA. With regard to his not having ex-

* J. S. Forrest: *Beama Journal*, 1939, **44**, p. 51.

perienced complaints with transformers below 1 000 kVA, it may be noted that such transformers are, for economic reasons, often installed very close to house property and only where foresight is exercised are any precautions taken against noise.

In welcoming Mr. Fleming's contribution, we desire to record our appreciation of the comprehensive and accurate sound transmission data originating from the work of the N.P.L. and published in such convenient form in the paper by the late Dr. Constable and Mr. Aston, to which we have referred.

We wish to endorse Mr. Ellis's view of the importance of the confirmation of laboratory findings by full-scale experiments and the need for regarding the installation as being at least as important as the transformer in considering noise problems. We are much interested in his suggestion that the idea of buried transformers should be re-examined from the standpoint of air-raid precautions.

Mr. Lacey's comments on the relation of noise level to kVA are of interest. In examining this matter we arrived at the index of approximately 4 in the relation between kVA and dimensions on theoretical grounds, but an examination of the dimensions of a large range of transformers from 60 to 75 000 kVA indicated that while the index was close to the value 4 for units of small and medium kVA, it appreciably exceeded that value for the larger sizes. Apart from the reason connected with the relation between sound wavelength and linear dimensions mentioned by Mr. Lacey, there are other reasons which make it unlikely that a constant index would apply. In collecting data to establish reasonable noise levels it would, therefore, seem advisable to utilize the results of noise measurement on a range of transformers rather than assume a value for the index. Mr. Lacey rightly points out that the idea of building a noiseless transformer by using core material of zero magnetostriction is not new. This is supported by the experience of one of the authors during a visit to the United States in December, 1934–January, 1935. The magnetostrictive properties of silicon steels were then being studied (possibly as a result of the work of Schulze referred to by Mr. Lacey) and the use of 6 % silicon steel, observed to have a low magnetrostriction effect, was under consideration for building transformers of low noise-level. The mechanical properties of this material were proving a serious practical obstacle. Experiments on transformer cores of a construction intended to minimize the generation of noise by magnetostriction were also seen.

We are glad to know that Dr. Billig's experience is in many respects in agreement with our own. The inconsistencies he points out in the relation between silicon content, magnetostriction value and noise level are within the limits of experimental error. The magnetostriction measurements were made on strip specimens. Among specimens of what is nominally the same material, considerable variation in magnetostriction value is found. Further, the noise measurements were made on ring, and therefore different, specimens. In addition, there is the error in the noise measurement. The tests simply show that, among the practicable core materials, none has appreciable advantage over the others. In Dr. Billig's experiments on how much of the noise in ring cores is attributable to magnetostriction and how much to joints, the observation that the noise from a jointless ring core magnetized to saturation could hardly be heard is difficult to explain. Tables 4 and 6 in the paper show that for a 15 in. diameter ring core with $B = 13\,000$, a noise level of the order of 40 phons is obtained, which, under negligible background noise conditions, is plainly audible and easily measured with a suitable meter. Further experiment would be needed, in our opinion, to ascertain conclusively the importance in normal cores of joint noise (i.e. the lateral vibration of the laminations due to cross flux at the joints) compared with that due to magnetostriction. However, our own experience points to the following conclusions. Experiment showed that at normal transformer densities a butt joint inserted in a ring core gave an increase in level of 10 phons or more, but with interleaved joints the increase was not more than 3 phons. The cores were tightly bound together with strong tape. With the more positive clamping available in a normal core, lateral vibration of the laminations at the joints is more effectively restrained, and the tests of Table 5 suggest that joint noise in a normal well-clamped core is unimportant. We think that the presence of joints in a normal core is more likely to be important in affecting the rigidity of the core than in causing joint noise. The general importance of core rigidity has been mentioned in our reply to Prof. Kapp. The lateral rather than end radiation of sound from the limb of a core, also observed by Dr. Billig, and, as noticed by us in one case, the greater radiation from the centre of the limb rather than from the region of the joints, suggests that a buckling motion due to differential magnetostrictive strain among the laminations may be present. This would give rise to a greatly increased radiation compared with that due to simple elongation of the limbs and suggests an explanation of the discrepancy pointed out by Dr. Billig. In fact it appears that this buckling effect can be so large and uncertain as to preclude the possibility of estimating from magnetostriction data the noise radiated by a core of normal construction. In regard to Fig. 3, it is, of course, necessary to allow space above and below the absorbers for oil circulation, but the effect of the bridging of the absorbers by the oil was checked, as stated on page 546.

The question of test procedure raised by Mr. Forrest is important and one on which agreement is desirable. It is rather too detailed a matter for present discussion. We have replied above to the question on the application of the absorber device to larger transformers. With regard to the reduction of noise level with distance, the 6-phon rule is stated with reservations for cases where it cannot be expected to apply accurately. The stationary-wave effects mentioned by Mr. Forrest imply obstructions of some kind in the sound field, which, of course, cannot be covered by any simple rule. We note that Mr. Mason has found approximate agreement with the 6-phon rule in certain cases.

In reply to Mr. Dadson, the value of 40 phons for the level outside a dwelling house at which complaints are liable to arise is based on those cases of which we have had direct experience. As already stated, it is probable that there will always be individual differences of opinion as to what level is considered tolerable. Further data on a defined basis for a number of cases would enable this

range of variation to be ascertained. The noise-abating measures found by Mr. Dadson to be adequate in borderline cases are of interest. We have used absorbent material in ducts with considerable effect. The reported relative quietness of the circular shell type of transformer, referred to in the paper, is certainly worth investigation. It is hoped that Mr. Redfearn's work on barriers and some other sound-field problems will be published shortly.

Mr. Alexander and Dr. Swaffield express interest in the magnetostriction measuring apparatus used by us. A full description, which we hope will be published in due course, is impracticable here but the main features are these. The apparatus takes a strip specimen and is of the mechanical-optical type, embodying a simple but effective device, which we have not seen described elsewhere, for obtaining the requisite sensitivity. With a given specimen in position, observations are reproducible to a few parts in 10^8 in terms of strain. Hysteresis loops can be examined in detail. The conditions of magnetization of the specimen are accurately defined. Water cooling inside the magnetizing winding is provided to minimize temperature effects. Mr. Alexander and Dr. Swaffield both comment on the magnetostrictive hysteresis curve of Fig. 1 of the paper being "practically identical" with one obtained by themselves and quoted by Prof. Kapp as Fig. B. While the general form of the two curves is similar there are obvious differences in the region of zero magnetostriction, which the experimental points of Fig. 1 show to be significant. The similarity in maximum extension is fortuitous, since another specimen of the same material (Table 3) shows 30 % greater extension. Even specimens cut from different parts of the same sheet have shown a difference of 30 % in magnetostriction value, and from different sheets 50 % or more according to the flux density in question. The piezoelectric indicator mentioned by Mr. Alexander should be useful where it is desired to record large numbers of magnetostriction hysteresis loops. In reply to his question on the 6 % silicon steel noise tests given in the paper, the magnetostriction in the sample used was not measured, as no strip specimens were available at that time. However, some strips of 6 % silicon steel have since been obtained and the magnetostriction effect on one of them, obtained with the apparatus referred to above, is shown in Fig. D. Sufficient strips were not available to build a core representative of normal construction, but it was interesting to find that with the small core built, no measurable or audible noise was present until a value of $B = 11\,000$ was reached, after which the noise level increased rapidly. It was noticed that the noise was considerably higher in pitch than that from a core of 4 % silicon steel, which is consistent with the character of the magnetostriction curve. The intensity levels of the components were too small to permit of sound analysis.

We are glad to note that Mr. Mason's experience confirms our own in many respects. We have not encountered a complaint at 15 phons inside premises, but possibly the consideration of a more complete range of data may suggest a lower figure than that of 30 phons which we have so far found adequate. The experiments on the effect of lining a tank with resilient material are of interest. Theory indicates that a great deal more compliance would be required to produce a given result in this way compared with the use of absorbers spaced away from the tank. With regard to the distance from a transformer at which noise observations should be made, we have, of course, encountered the background noise difficulty in works testing mentioned by Mr. Forrest, which often compels a short distance. But we agree with Mr. Mason in preferring a greater distance for other reasons. The ideal would be to test under negligible background noise conditions, enabling distances to be used capable of giving more informative results. The question of whether the noise emitted from radiators is important when the tank is placed in a soundproof enclosure must depend, to a considerable extent, upon the sound insulation of the enclosure. We are interested to note that Mr. Mason found that with a sound insulation of 30 phons the noise from the radiators was negligible. More experimental data on this point would be useful.

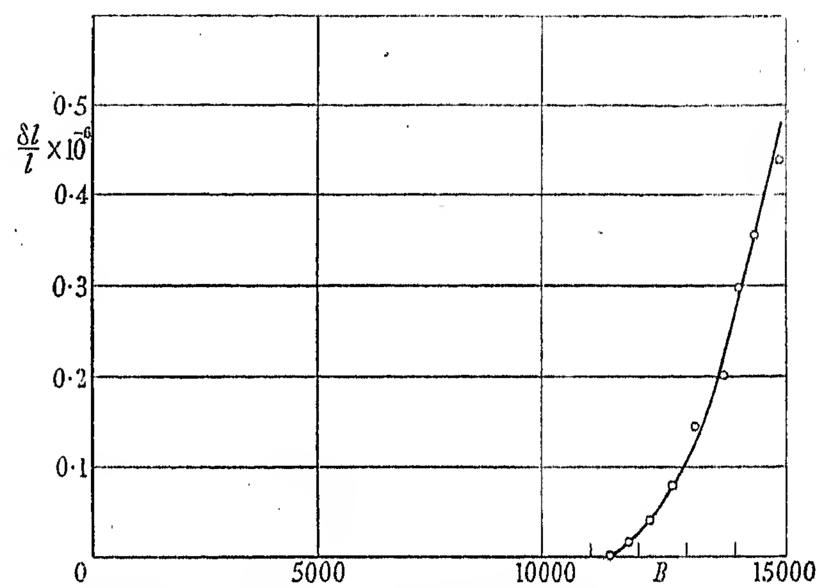


Fig. D

We had planned some experiments for this purpose but, owing to the demands of war activities, have been unable to give the matter further attention. The damping effect of oil between laminations mentioned by Mr. Mason is illustrated by Table 6 of the paper, where a reduction of 11 phons due to this cause is obtained with a small core of normal construction.

We have already replied to Dr. Swaffield regarding the magnetostriction apparatus used by us. The direction in which the hysteresis loop is traversed is indeed a curious effect and we were at first disinclined to accept it. However, after a careful check of experimental procedure, the effect was confirmed. Dr. Swaffield's objection to the term "magnetostrictive force" is correct for ideal conditions. He tacitly assumes perfect uniformity of field and magnetic material and absence of constraint. If any one of these conditions is not fullfied, the magnetostrictive strain which would otherwise occur is resisted and stresses inevitably arise, quite apart from stresses due to inertia. All these effects are present in a normal core. Therefore, although the stress is elastic, the strain causing it is magnetostrictive and hence our inclusive term "magnetostrictive force." We point out on page 544 that the sound from a single ring punching is

radiated axially and not radially. We have already suggested an explanation in reply to Prof. Kapp. Considering magnetostrictive strain only, the harmonics of the double frequency are dependent on the departure of the magnetostriction curve from a parabola, as Dr. Swaffield points out. This would also apply to the vibration and noise radiated if the mode of vibration were one of simple elongation. In normal cores other modes of vibration, such as the buckling motion referred to, may be excited, and it would be necessary to show that in each case the response of the system was linear. Even if this were found to be so, the problem of developing a steel with an accurately parabolic law does not appear to be obviously simpler than that of securing zero magnetostriction. However, we are quite in agreement as to the desirability of pursuing the study of fundamental phenomena underlying transformer noise. We can see no reason why this should not proceed concurrently with the examination and development of more immediately available measures, such as those with which the present paper deals.

In reply to Mr. Rippon, we have not gone out of our way to investigate cases where legal proceedings are likely to ensue. In the cases of which we have had experience, we have not found the legal profession ready to accept as evidence the results of noise measurements, but rather to rely upon what were, in one case, called "commonsense grounds." In this case measurement had shown that the level outside the nearest house to the source complained of was 44 phons. This was not accepted as evidence. The judge adjourned the court to listen to the noise and advised the parties to come to an agreement as, in his opinion, there was no cause for complaint. On the other hand, steps have been taken by the Ministry of Transport (see "Noise in the Operation of Mechanically Propelled Vehicles," Interim Reports I, II and III, and Final Report, H.M. Stationery Office) to deal with the noise of motor vehicles on a quantitative basis, and had it not been for the war there is little doubt that the recommendations made would have been adopted legally. One important feature of the proposals is the fixing of a limit in phons, together with a tolerance of 5 phons, to be withdrawn after two years. This would enable gross cases of nuisance to be dealt with immediately. It would also give manufacturers time to improve their products in regard to noise, and the legal and police authorities time to correlate the new quantitative standard with their existing practice. To apply "all known noise-abatement measures" to a transformer installation may have been good advice 15 years ago. The whole purpose of the paper is to avoid such indiscriminate use of measures, irrespective of their efficacy, in order to secure a safe legal position and to replace such practice by the application of measures designed to be technically adequate, which should go far towards avoiding legal issues altogether. Mr. Rippon is incorrect in stating that the flux density values of Fig. 2 are higher than those obtaining in normal practice for commercial transformers. Almost all commercial power transformers come within the range $B = 10\,000$ to $B = 15\,000$, the value of $B = 13\,000$ being very common. Mr. Rippon, in assuming a distinction between equivalent loudness and "nuisance," should remember that equivalent loudness is ultimately based on a subjective estimate, even if measured by an objective meter. As stated in the paper, it has not so far been conclusively demonstrated that such a distinction exists. We consider Mr. Rippon's conclusions on the absorber method altogether too sweeping. The required increase in tank dimensions is only a few inches, and, although such increase might not be allowable on the largest transformers owing to railway loading gauge restrictions, it would for most other sizes be quite unimportant. The absorber method is intended for more substantial noise reductions than are obtainable by a 20 % reduction in flux density. It may be true of cases within Mr. Rippon's experience that complaints are not common with transformers of less than 1 000 or 2 000 kVA, but it is not generally true. As to the effect of rating, a 500-kVA transformer has a noise level of only about 7 phons less than one of 5 000 kVA. The variation due to installation conditions covers a far larger range. There have been many cases of transformers of 1 000 kVA or less being installed in the open under such conditions that complaint was not surprising. With regard to Mr. Rippon's question on fire risk with absorbers, the film we use is non-inflammable.

In reply to Mr. Orchard, we have not compared the noise levels of normal cores with butt and interleaved joints. His point about the design of resilient supports where the centre of gravity of the transformer is off the centre line is important. In reply to Mr. Turnbull, we doubt whether the use of corrugated tanks would appreciably affect the noise radiated.

In reply to Mr. Mann, the factors determining the attenuation of enclosures, including lack of air-tightness, whether due to ventilating holes or other cause, are given in the paper.

Mr. McBain's very constructive contribution is welcome. He rightly calls attention to the lack of foresight in regard to noise shown in the arrangement of some transformer installations and the attributing of the cause of complaint solely to the transformer, even though the latter may have quite a normal noise level. As we have already pointed out, the influence of installation conditions covers a far greater range than the variation in level among commercial transformers. The examples quoted by Mr. McBain are of special interest, particularly in regard to the very satisfactory results obtained. We note that he has found the use of flexible pipe connections between radiator and tank unnecessary and that a considerable attenuation may be obtained by planting trees and shrubs round the transformer.

In reply to Mr. Kidd's question on the noise from fans, apart from using low-speed fans noise can be limited very effectively by providing short sound-absorbing ducts at inlet and outlet, the ducts containing suitably disposed sound-absorbing material which will withstand outdoor conditions.

CERAMIC INSULATIONS FOR HIGH-FREQUENCY WORK*

By W. G. ROBINSON, B.Sc.Tech., Associate Member.†

(*Paper first received* 22*nd April, and in revised form* 14*th October,* 1940.)

SUMMARY

During the past few years ceramic materials with properties especially suited to working at radio frequencies have been developed. The present paper contains a brief account of the manufacture of such materials, followed by a discussion of their mechanical and electrical properties.

It is pointed out that many of the discrepancies in previously published data may be explained by the difficulties of the measurements and by the variation of some of the quantities to be measured with factors not always sufficiently controlled or specified. The differences in values obtained on test samples and those which may be realized practically are emphasized. The paper concludes with a brief account of the application of ceramic materials in the radio industry.

CONTENTS

(1) Introduction.

(2) Manufacture.

(3) Electrical and Mechanical Properties.
  (*a*) Power factor.
  (*b*) Permittivity.
  (*c*) Electric strength.
  (*d*) Mechanical strength.
  (*e*) Thermal expansion.

(4) Applications.
  (*a*) General insulation.
  (*b*) Condensers.
  (*c*) Coils.

(5) Conclusions.

Acknowledgments.

Bibliography.

(1) INTRODUCTION

The essential requirements of an insulating material for radio-frequency work are:—

(1) The power loss must be small at the frequency under consideration.

(2) For some applications the permittivity should be high.

(3) The material must be capable of being made in any desired shape, and for some purposes these shapes must be made to considerable dimensional accuracy.

(4) The material must be rigid and stable so that its dimensions and properties are unaffected by time or by the temperature changes encountered in service.

Electrical porcelain meets the last two requirements admirably, but the power loss is high and the permittivity has only a moderate value. It has been found, however, that, by making changes in the composition, ceramic materials can be produced with satisfactory electrical properties at radio frequencies without loss of their good mechanical characteristics.

These materials have been developed in Germany, and many papers with tables of technical data have been published in that country.[1] Considerable interest has also been shown here and ceramic materials have been mentioned in papers by H. A. Thomas, W. Jackson, and J. F. Gillies.[2] The paper by Jackson contains an excellent review of the subject.

High-frequency insulating material is required either for insulation, i.e. for separating and supporting the current-carrying parts of circuits, or for condenser dielectrics. In the first case the criterion is minimum power loss, which is given by the material having the lowest value of $K \tan \delta$. In the second case the material having the lowest value of $\tan \delta / K$ will produce the best condenser. These conflicting requirements have led to the development of two groups of materials which have come to be known as the steatite group and the rutile group. The steatite group materials have moderate values of permittivity and low power factors and are used for insulation, whilst the rutile-group materials, which have high permittivities together with low power factors, are used for condenser dielectrics.

The Steatite Group

The basic substance of this group is steatite, a hydrated magnesium silicate $3MgO, 4SiO_2, H_2O$ which occurs in nature as soapstone or talc. This is converted into magnesium silicate $MgSiO_3$ on firing.

Two fairly clearly defined classes of material have been developed in this group. The first, which is more commonly used, consists of materials containing up to 70 % of steatite, the remainder being clays and fluxes. In the second, which, generally speaking, has lower power factors, the percentage of steatite is reduced by the addition of magnesite. On firing, the magnesite, $MgCO_3$, is converted into magnesium oxide, the change being accompanied by a large reduction in volume, or "shrinkage" as it is termed in the industry. This introduces manufacturing difficulties and makes the attainment of accurate dimensions almost impossible, so that insulators manufactured in this type of material often have to be ground to size after firing.

The Rutile Group

The materials of this group owe their high permittivities to the presence of rutile, a titanium dioxide,

* The Papers Committee invite written contributions, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Contributions (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† Bullers, Limited.

in the mixture. By using high-plasticity binders it is possible to work successfully with mixtures containing over 90 % of rutile, thereby obtaining permittivities as high as 90. As will be explained in a later paragraph under the heading of "Permittivity," materials containing large percentages of rutile have high negative temperature-coefficients of permittivity. When this is undesirable it is necessary to reduce the rutile content, and this is done by adding to the mixture materials which are converted into refractory oxides on firing. Alternatively, the rutile may be combined with an alkali earth to produce magnesium titanate which is then worked by the usual ceramic processes.

Rutile materials have accordingly developed along two main lines, one type aiming at the highest permittivity and the other at a permittivity which is independent of temperature. Mixtures intermediate between these two main types are also used.

(2) MANUFACTURE

In considering the use of ceramic materials a knowledge of the manufacturing processes involved is an advantage in comparing the merits of various designs.

The raw materials are first brought to a fine state of division by crushing and grinding before being mixed in the correct proportions and ground together under water in ball mills. The resulting creamy liquid, known as slip, is then treated in filter presses to remove most of the water, leaving cakes of plastic, clay-like, material.

In the manufacture of large insulators the cakes from the filter presses are passed through pug mills to render the material more homogeneous and plastic. The required shape is then produced by working roughly to shape on the potter's wheel and subsequently turning in a lathe, or by a vertical turning process known as jollying in which the clay, held in a plaster mould which gives the outside shape, is rotated past a tool which produces the inside shape. These two processes are obviously only suitable for the production of solids of revolution. Rods and tubes of circular or irregular cross-section are made by extruding the plastic mass through suitable nozzles, whilst shapes which cannot be made by rotary or extrusion processes may be made by casting the liquid slip in plaster moulds. All the above processes are known as plastic processes.

Small insulators for use at low voltage are made by a pressing process. The cakes of clay from the filter presses are dried and pulverized. The powder so formed, with or without the addition of a little oil or water, is then pressed in steel dies to produce the desired shape. This process is obviously suited to quantity production and most of the small insulating parts required in the manufacture of components and complete apparatus are made in this way.

The shaped articles are slowly dried to remove most of the free water before firing at temperatures of from 1 250 to 1 400° C. The removal of water during the drying, and the physical and chemical changes occurring in the firing, cause a shrinkage which varies from 8 % to as much as 30 %, depending on the composition. This has to be allowed for in the shaping process and of course makes the attainment of fine dimensional tolerances difficult. The larger insulators made by the plastic processes can usually be made to tolerances of ± 2 %, but the smaller pressed pieces can often be made to ± 1 %. If finer tolerances are necessary they can only be obtained by grinding the material after firing. Owing to the extreme hardness (7–8 mohs scale) this is expensive and should be avoided whenever possible. In this connection it might be pointed out that if engineers would seek the co-operation of the insulator manufacturers in the design stage it would often be possible to suggest simple modifications which would avoid expensive work on the fired pieces.

(3) ELECTRICAL AND MECHANICAL PROPERTIES

The electrical and physical properties of ceramic materials have been published and mentioned in several papers.[1, 2] The values quoted in many cases are those obtained by testing specially prepared samples under conditions bearing little relationship to practical conditions. It is therefore proposed to consider the more important properties, giving values which can be realized in commercially produced materials under conditions similar to those encountered in practice.

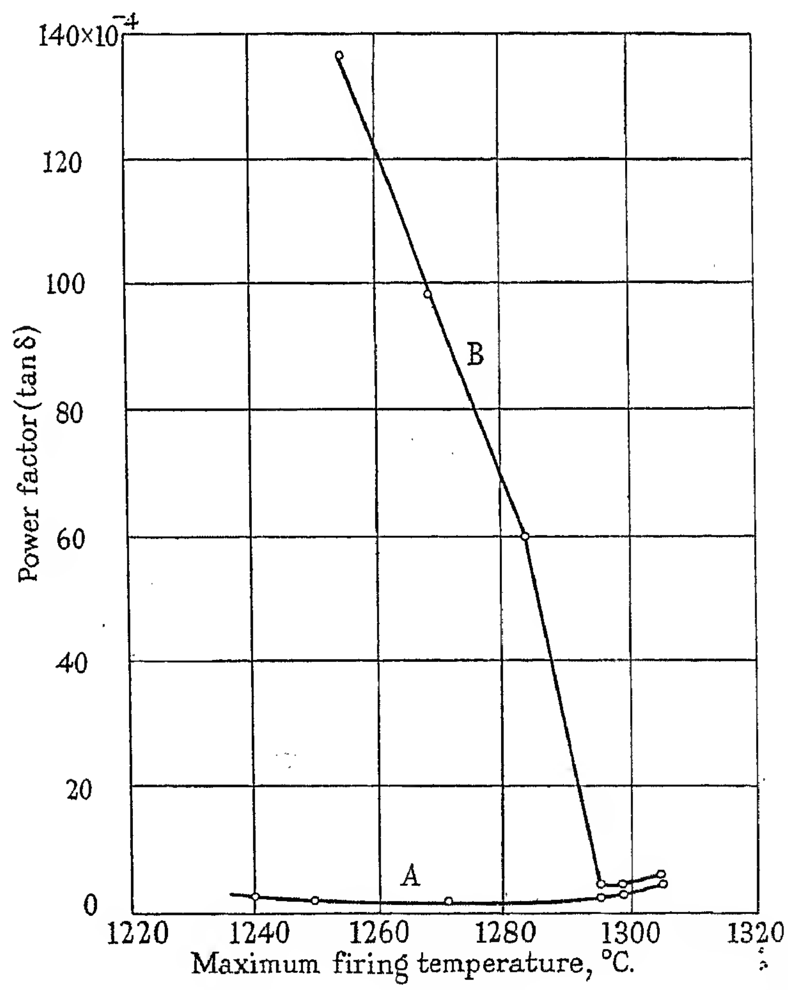


Fig. 1.—Variation of power factor of a steatite group material with maximum firing temperature (frequency 1 Mc./s.).

A. In dry atmosphere over calcium chloride.
B. In atmosphere of 75 % relative humidity.

(a) Power Factor

The power factor of insulating materials is usually determined by taking a sample disc to which electrodes are applied and measuring the power factor of the condenser so formed. The technique of such measurements at radio frequencies has been previously described.[3] In testing ceramic materials the properties of the test

condenser do not necessarily represent the properties of the dielectric and it is important to take precautions if accurate and consistent results are to be obtained. Surface moisture films develop on ceramics, glass and certain other materials under ordinary atmospheric conditions. These moisture films are stable and their laws

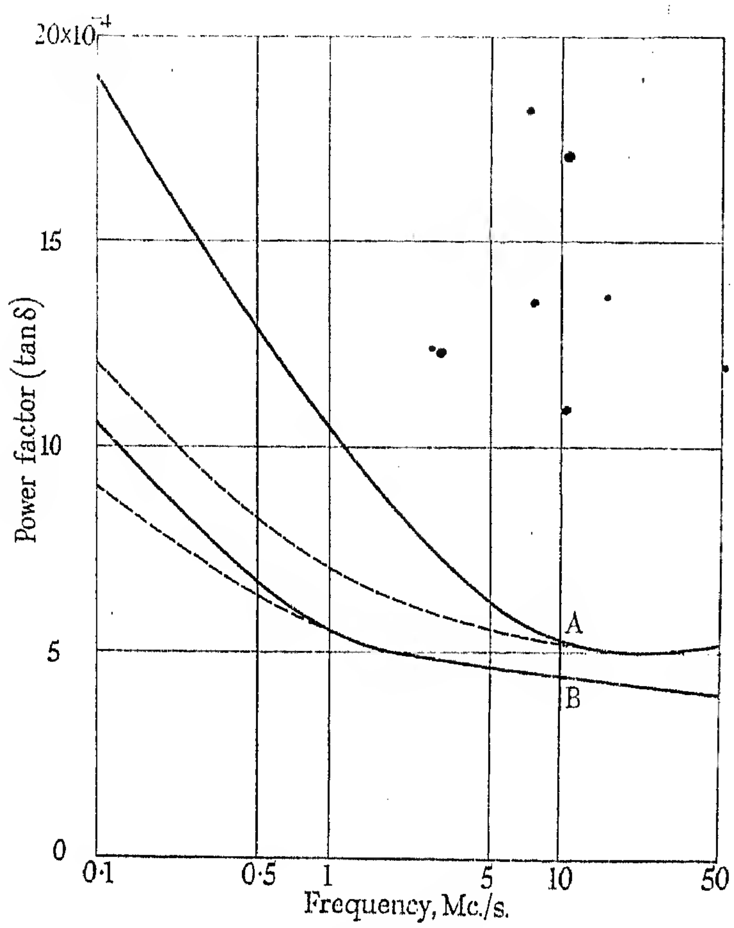


Fig. 2.—Effect of humidity on the power factor of ceramic materials.

A. Steatite group material.
B. Rutile group material (high permittivity).
——— Tests at 75 % relative humidity.
- - - - Tests in dry atmosphere over calcium chloride.

of formation and their electrical resistance have been studied.[4] Surface leakage occurs through the moisture film and causes an increase in power factor of the test condenser, especially at the lower frequencies (below 1 Mc./s.). In order to reduce this effect, the diameter of the electrodes should be a few millimetres less than the diameter of the test disc. Also, it is of great importance that the test disc should not be touched by the hand, since a minute trace of perspiration will greatly increase the conductivity of the moisture film.

Atmospheric moisture also affects the power factor of ceramics which are not properly vitrified, by penetrating into the small interstices in the material. Ceramic materials are not homogeneous, but consist of a crystalline structure bonded by a glassy matrix. The glassy bond develops during the firing and spreads slowly through the material. If the temperature or period of soaking is insufficient the material will be porous, while if the temperature is too high there is a danger that gases will be evolved, forming bubbles and imparting a vesicular structure to the material. In either case atmospheric moisture may penetrate the material, causing a rapid increase in power factor, especially at the lower frequencies. This is shown in the curves of Fig. 1, which give the power factor of discs of a steatite group material which had been fired to various maximum temperatures, the period of firing being the same in each case.

There are many references in the literature dealing with ceramics to the effect of moisture on the power factor[5] and it is sometimes recommended that tests should be made *in vacuo* or the test disc heated and perhaps coated with wax or other moisture-resisting substance. A consideration of Fig. 1 will show that this is dangerous, since a poorly vitrified material, which would have a high power factor under working conditions, would not be detected.

It is therefore recommended that tests be made in a humid atmosphere and that the test frequency be not too high, 1 Mc./s. being suitable. This is easily arranged by testing in an enclosure in which the air is circulated over moistened crystals of sodium chloride to give a relative humidity of about 75 %. Where a type of electrode which prevents access of the atmosphere to the surface of the disc is used (e.g. tin foil applied with vaseline or an accurately ground disc clamped between metal electrodes) the disc should be exposed to the humid atmosphere for some time before fitting the electrodes.

The variation of power factor of well vitrified ceramic materials with humidity is quite small at frequencies

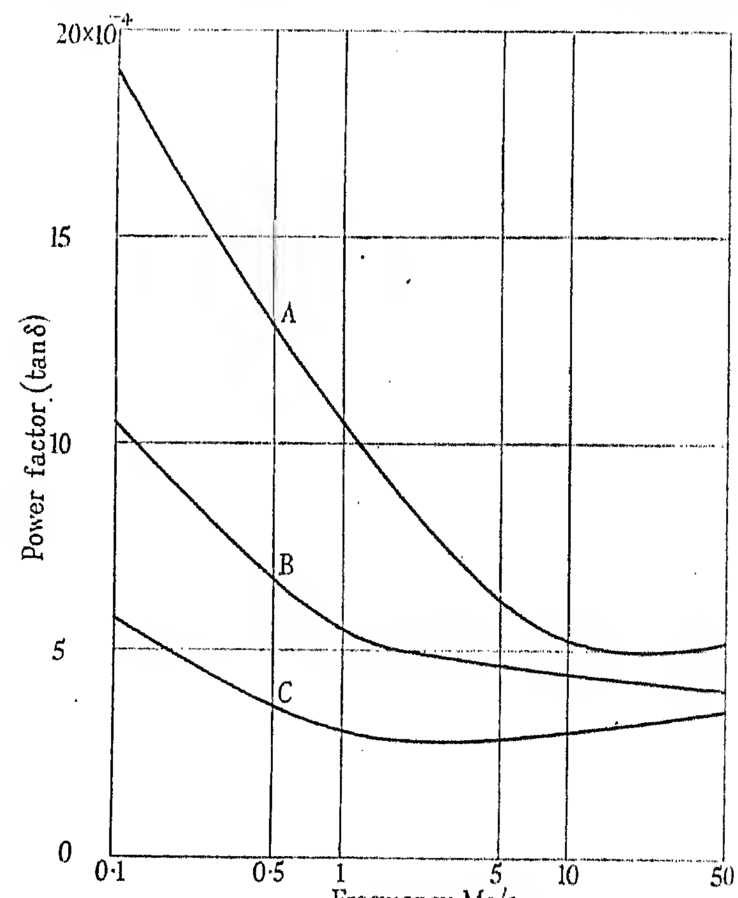


Fig. 3.—Variation of power factor with frequency (75 % relative humidity).

A. Steatite group material.
B. Rutile group material (high permittivity).
C. Rutile group material (low temperature-coefficient of permittivity).

above 1 Mc./s. and Fig. 2 shows the results obtained on typical materials of the steatite and rutile groups. Previous investigators have reported larger variations than those shown, the differences being probably due to differences in the vitrification of the materials.

The power factor of ceramic materials does not vary greatly with frequency over the range of 1 Mc./s. to 50 Mc./s., but below this range there is usually a rapid

increase in the power factor with decreasing frequency. Values for typical materials are given in Fig. 3.

As with most other materials, the power factor of ceramics generally increases with temperature. At frequencies below 1 Mc./s. where conduction effects are more important there may be a fall in power factor with increasing temperature.

(b) Permittivity

The occurrence of high permittivity in solid insulating materials has been discussed in a paper by F. C. Frank,[6] where it is shown that high permittivity only occurs when both the electronic polarizability of the constituent ions and the atomic polarizability of the compound are high. This condition is satisfied in rutile, which contains the highly charged titanium and oxygen ions and in which the closely packed crystal lattice has a high atomic polarizability. Permittivity depends on the closeness with which the material is packed, or the density, and Table 1 gives values of density and permittivity of rutile, steatite and the finished ceramics.

Table 1

Material	Density	Permittivity
Magnesium silicate $MgSiO_3$	3·0	—
Steatite ceramics	2·7	6·0–6·5
Steatite magnesite ceramics	2·8	7·5
Rutile	4·21	114
High-permittivity rutile ceramics	3·9	80
Low-temperature-coefficient rutile ceramics	3·1	10

The variation of permittivity with temperature depends on the relative contributions of electronic and atomic polarization to the permittivity. Electronic polarization is almost independent of temperature, so that in a material where this is the predominant factor the permittivity will decrease with increasing temperature owing to the decrease in density. The temperature coefficient of permittivity will be given by the approximate theoretical formula:—

$$\text{Temperature coefficient of permittivity} = \frac{\text{Coefficient of linear expansion} \times \text{Permittivity}}{\text{Density}}$$

which has a value of -300×10^{-6} for rutile.

For steatite and the ceramic materials the permittivity arises mainly from atomic polarization, which increases with temperature owing to expansion of the crystal lattice. The temperature coefficients of the steatite group materials are, therefore, positive. Since the contribution of atomic polarization is usually small compared with electronic polarization the steatite materials have only moderate values of permittivity.

It will be appreciated that in the rutile group materials, which consist of a mixture of rutile and a ceramic binder, the permittivity and its temperature coefficient will vary with the relative proportions of the constituents. The manner of this variation has been investigated by W. Soyck, whose curves are reproduced in the paper by W. Jackson mentioned above. An important feature is that mixtures containing about 25 % of rutile have permittivities independent of temperature, the values being 10 to 15.

The measurement of permittivity presents little difficulty. The capacitance of a test disc, preferably with burnt-on silver electrodes, is measured and the permittivity calculated, making a suitable correction for edge effect. Care should be taken in manufacturing the test disc to ensure that it is really representative of the finished products.

The temperature coefficient of permittivity of a material is not measured directly but is obtained from the temperature coefficient of capacitance of a condenser of which the material forms the dielectric. The two quantities are related by the linear coefficient of thermal expansion. In measuring the temperature coefficient of capacitance the test disc should preferably be provided with burnt-on silver electrodes. This avoids the non-cyclic variations, due to relative movements, which are liable to occur when other forms of electrode are used.

Table 2

CHANGE IN CAPACITANCE WITH TEMPERATURE OF CERAMIC DISCS WITH BURNED-ON SILVER ELECTRODES

Material	Permittivity	Change in capacitance, $\Delta C/C$ per deg. C.
Steatite group	6·0	$+ 90 \times 10^{-6}$
Rutile group (high permittivity)	80	$- 610 \times 10^{-6}$
Rutile group (low temperature coefficient of permittivity)	10	$+ 10 \times 10^{-6}$

Table 2 shows the variation of capacitance of various ceramic materials over a temperature range of 15°–75° C.

(c) Electric Strength

The electric strength is seldom a limiting feature in the practical application of ceramic materials. In the case of high-voltage insulators the working stress is frequently limited by power-loss considerations, and in the case of condensers, where the material is kept as thin as possible in order to obtain high capacitances with small dimensions, manufacturing difficulties usually determine the minimum thickness which can be used.

The ceramic materials follow the general rule that high permittivity is associated with low electric strength. Steatite group materials have electric strengths of about 800 kV/in. for pieces made by plastic processes, and 250 kV/in. for pressed pieces, the thickness in each case being $\frac{1}{4}$ in. The strength varies approximately inversely with the square root of the thickness. The electric strength of the rutile materials ranges from 25 % to 40 % that of the steatite materials, larger percentages of rutile being associated with lower electric strengths.

Temperature has a considerable influence on electric strength, the value being reduced to about 80 % at

90° C. and 10 % at 250° C. compared with that at normal room temperature.

(d) Mechanical Strength

The measurement of the mechanical strength of ceramics is a matter of some difficulty due to the hard unyielding nature of the materials. Concentrations of stress at the points of application of the load cause wide variations in the results obtained. Tests are of no value for purposes of comparing different materials unless standard test pieces and test methods are used. Even so, the values recorded using small test specimens are much higher than those which can be realized in the manufacture of insulators. For this reason the values of mechanical strength given in Table 3 are obtained from tests on typical insulators and not on special test pieces.

Table 3

MECHANICAL STRENGTH OF A STEATITE GROUP MATERIAL

Method of manufacture	Ultimate stress (lb./sq. in.)
Plastic process ..	2 000–3 000 in tension 200 000 in compression 4 500–7 000 in bending
Pressing process ..	1 200–1 500 in tension 60 000 in compression

As condenser dielectrics are not usually called on to support mechanical loads, values are not given for the rutile materials.

In designing insulators it is necessary to avoid concentrations of stress at the point of attachment of metal fittings and wires, if the full strength of the material is to be developed. Even in the small pressed pieces it is a great advantage to allow a little resilience in the metal parts so that any slight variation in dimensions will not cause undue stressing and possibly cracking of the insulator.

Table 4

THERMAL EXPANSION OF CERAMIC MATERIALS

Material	Linear coefficient of expansion, $\Delta l/l$ per deg. C.
Steatite group	$8 \cdot 2 \times 10^{-6}$
Rutile group (high permittivity) ..	$10 \cdot 8 \times 10^{-6}$
Rutile group (low temperature coefficient of permittivity)	$9 \cdot 6 \times 10^{-6}$
Normal electrical porcelain	$5 \cdot 0 \times 10^{-6}$

(e) Thermal Expansion

The low-loss steatite and especially the rutile materials have higher thermal expansions than normal electrical porcelain, as will be seen from the values in Table 4.

Certain clay-steatite materials produce ceramics of very low thermal expansion (1 to 2×10^{-6}), but these have power factors of 70 to 40×10^{-4} at frequencies of 1 to 50 Mc./s.

(4) APPLICATIONS

It is clear from what has been written above that a wide range of ceramic materials is available and by choice of the correct type it is possible to meet most of the requirements of the radio industry. A brief review of what can be done with the new ceramic insulations will now be given.

(a) Insulators

Large pieces such as aerial tension insulators, mast base compression insulators, feeder line supports, bushing insulators and stand-off or pedestal insulators are made by plastic processes from steatite group materials. Where the insulator is for use out of doors a glazed surface is an advantage since dirt does not adhere easily to the surface and when cleaning does become necessary it is easy to carry out. It might be pointed out here that the materials themselves are non-hygroscopic and do not depend on the film of glaze to keep out moisture.

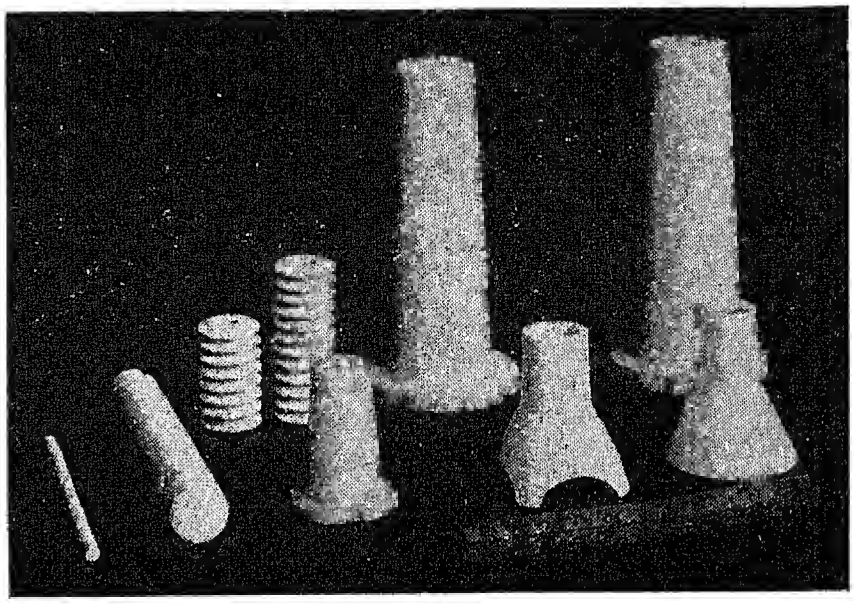


Fig. 4.—A group of plastic-process insulators.

Steatite group materials are much more difficult to handle in plastic process manufacture than electrical porcelain, and insulators previously produced in the latter material cannot always be made in low-power-factor ceramics. Fig. 4 shows a group of plastic-process insulators made from steatite group materials.

In insulators for use at high radio-frequency voltages the parts in contact with metal fittings should be provided with a conducting layer in electrical connection with the metal fitting in order to reduce discharges and local heating. This is easily provided by the well-known metal spraying processes or by the silvering process to be described in the paragraph on condensers.

Small insulators such as valve bases and holders, terminal strips and condenser end plates, to mention a few, are made by the pressing process. In many cases the insulator in effect forms a jig on which the component is assembled, and in such cases fine tolerances in dimensions are necessary. Fig. 5 gives an idea of the intricate pieces that can be made in this way.

(b) Condensers

An important feature in the manufacture of ceramic condensers is the ease with which silver electrodes can be applied. A suspension of silver oxide in a suitable medium such as cellulose lacquer, or other type of silver glaze, is painted or sprayed on to the surface and the article fired to a temperature of 600–700° C. Connecting wires may be soldered directly to the silver coating. Since relative movement of the dielectric and electrodes is impossible with this form of construction, and the dielectric material itself is stable, such condensers are almost perfectly cyclic when subjected to temperature changes, and secular changes in capacitance are negligible.

When variation of capacitance with temperature is not important very compact condensers can be made by using a high-permittivity material pressed into the form of small discs or cups or extruded in the form of thin-walled tubes. A capacitance of 100 $\mu\mu$F can be obtained in a space of 1 cm^3. The high negative temperature-coefficient of this type of condenser can be turned to advantage, for in some cases it is possible to compensate for the frequency drift in a circuit arising from the warming-up of valves and coils by using such a condenser suitably disposed with regard to the other components.

Where constancy of capacitance with temperature is important this may be brought about by using a rutile material of the low-temperature-coefficient type or by a combination of condensers of positive and negative temperature coefficients. Fig. 6 shows the variation with temperature of the power factor and capacitance of a condenser made up with a low-temperature-coefficient rutile material. The sample tested was a disc approximately 5 cm. diameter with burnt-on silver electrodes and a capacitance of approximately 50 $\mu\mu$F. It was subjected to a number of thermal cycles between 15° and 75° C. and it will be seen that the behaviour under these conditions is almost perfectly cyclic. This is an important feature in constructing circuits where frequency variations must be kept within narrow limits and bulky temperature-controlled ovens are impracticable.

Another type of condenser which can be successfully made with ceramic materials is the trimmer condenser. A typical construction is shown in Fig. 7, where the rotor (1) consists of a thin disc of rutile material and the stator (2) is made of a low-loss steatite material. The contact surfaces of the rotor and stator are ground flat and the upper surfaces of both rotor and stator are provided with silver electrodes as shown. The capaci-

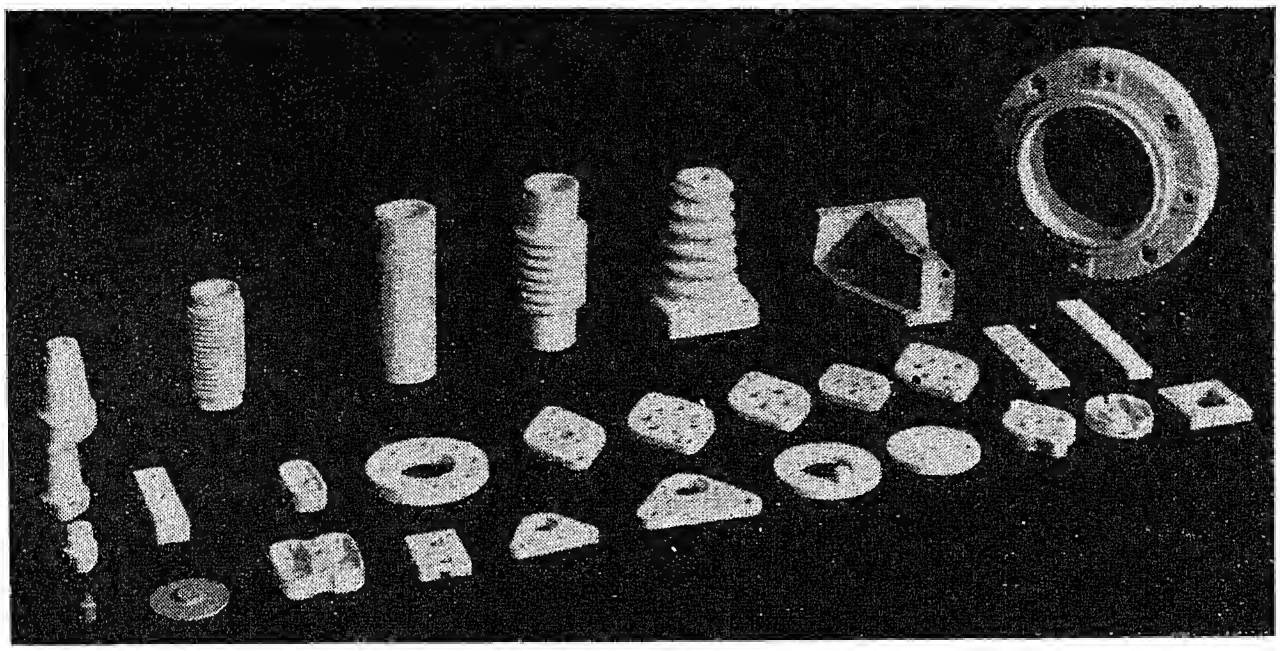


Fig. 5.—A group of pressed insulators.

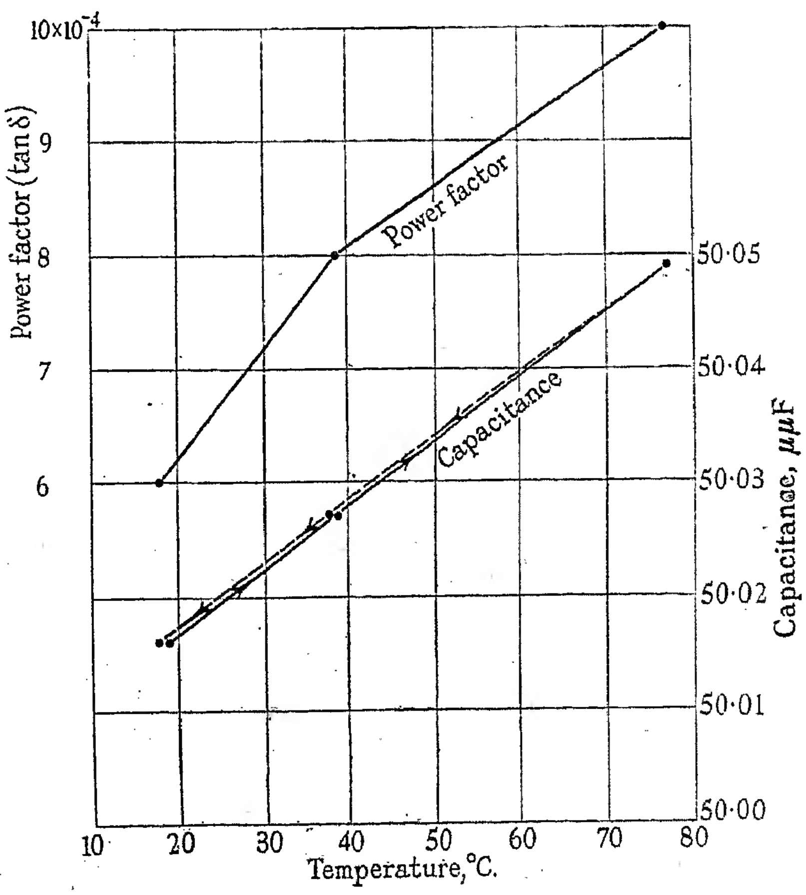


Fig. 6.—Variation of capacitance and power factor of a rutile group material with temperature (frequency $=10^6$ c./s.).

tance is adjusted by turning the rotor, there being enough friction to ensure that the setting is not disturbed accidentally.

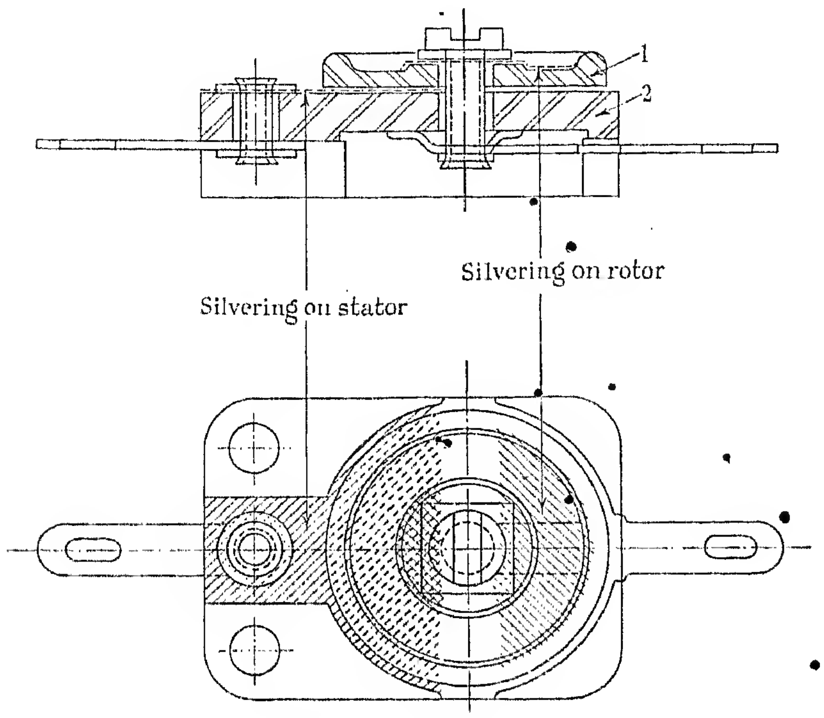


Fig. 7.—Ceramic trimmer condenser. Typical construction.

The author has carried out a series of tests on a small trimmer condenser of foreign origin which had a capacitance of 50 $\mu\mu$F and 8 $\mu\mu$F at maximum and minimum settings. The power factor was the same at both settings and is shown in Fig. 8. The variation of power factor with humidity in the sample tested was great and indicates that the rotor material was not well vitrified.

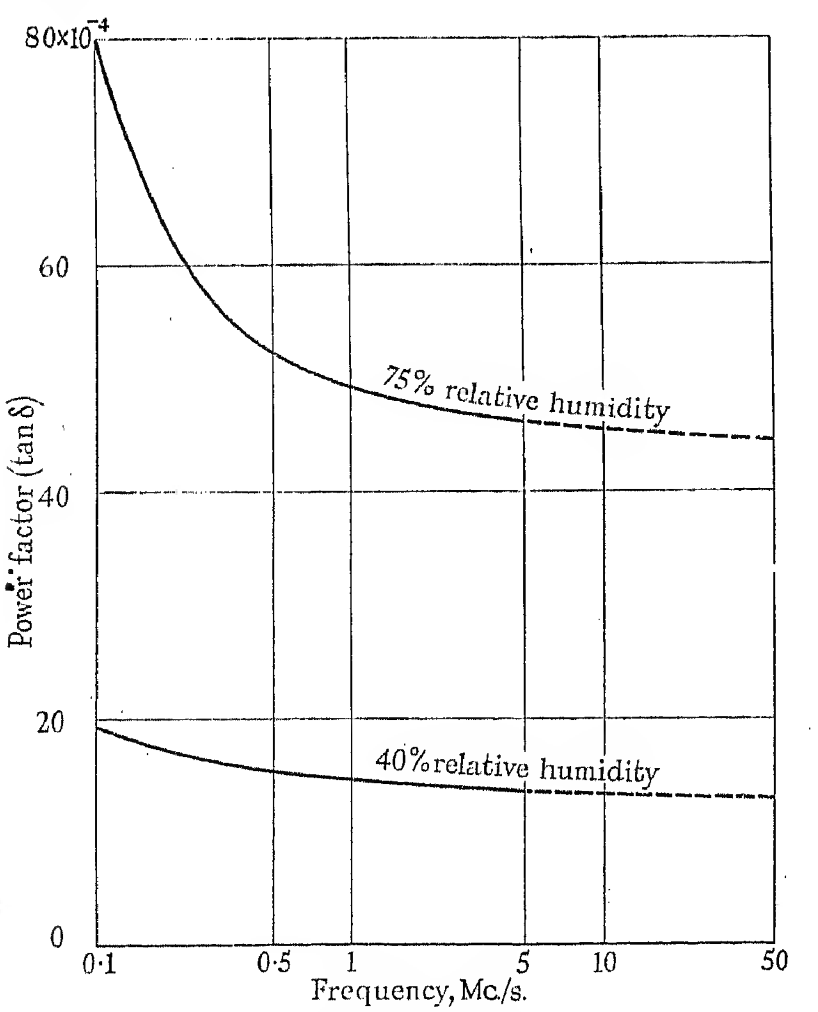


Fig. 8.—Ceramic trimmer condenser. Variation of power factor with humidity.

In trimmer condensers of this type the minute air film which exists between the rotor and stator is in series with the solid dielectric. It is to be expected, therefore, that the temperature coefficient of capacitance will be less than that for a test disc silvered on both sides. This is confirmed by the tests shown in Fig. 9, from which it is seen that the temperature coefficient of capacitance is about -560×10^{-6}. There is also a greater non-cyclic variation in capacitance than is shown by the tests recorded in Fig. 6.

Another type of trimmer condenser has two rotors

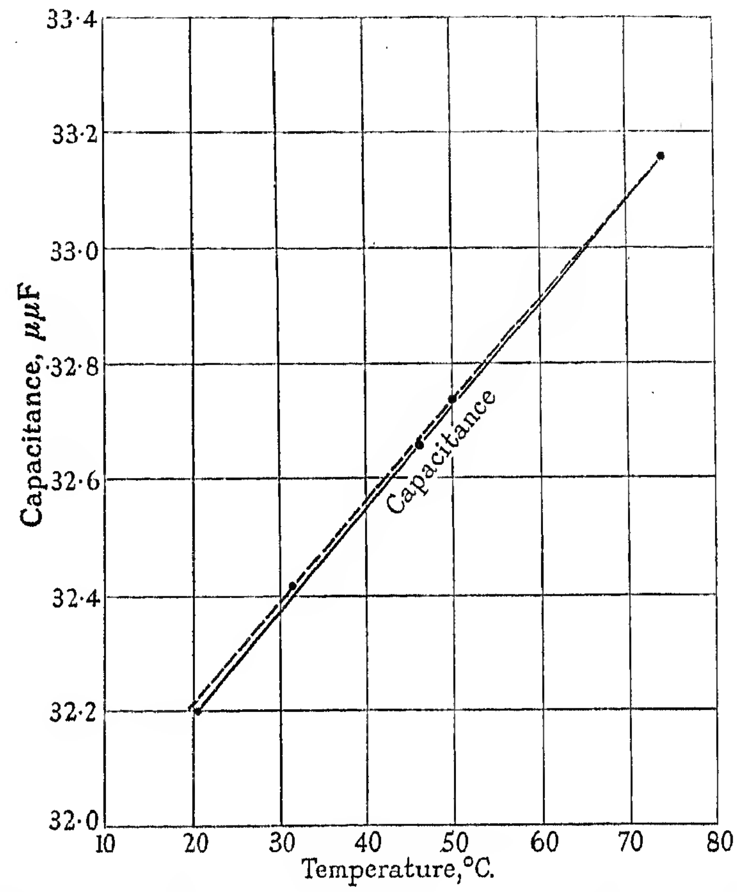


Fig. 9.—Ceramic trimmer condenser. Variation of capacitance with temperature.

attached to the same spindle and mounted on opposite sides of the stator. One disc is made of a rutile material and the other of a steatite material, the thicknesses being in the inverse ratio of the permittivities. The silvered electrodes are so arranged that as the rotors are moved the capacitance remains sensibly constant and its temperature coefficient varies continuously from a positive to a negative value.

(c) Coils

Coils of conventional design may be made by using ceramic formers with slots or helical grooves for the reception of the windings.

Coils showing very small change of inductance with temperature are constructed by depositing silver coatings directly on a ceramic former, the coating being reinforced by electroplating to give the necessary conductivity. The temperature coefficient of coils of this type is governed largely by the thermal expansion of the former, and can be reduced to a minimum by using the low-expansion clay steatite mixtures. Coils of this type when associated with ceramic condensers of the appropriate characteristics produce oscillatory circuits of great constancy and stability.

(5) CONCLUSIONS

Developments in radio technique have led to a demand for insulating materials and components having great stability and behaving in a cyclic manner when subjected to temperature variations. Ceramics are inherently suited to meet these requirements and can be produced with electrical characteristics at high frequencies which compare very favourably with those of any other type of material.

There are considerable difficulties in assessing and measuring both the electrical and mechanical characteristics, but if attention is paid to the points mentioned there should be no difficulties in comparing different materials or in deciding on values which may safely be used for design purposes.

Acknowledgments

The author wishes to thank the directors of Bullers, Ltd., for permission to publish this paper, and his colleagues on the staff of that Company for assistance in its preparation.

REFERENCES

(1) (*a*) E. A. SCHÖNBERG: *Elektrotechnische Zeitschrift*, 1933, **23**, p. 543.
(*b*) W. WEICKER: *ibid.*, 1933, **23**, p. 545.
(2) (*a*) H. A. THOMAS: *Journal I.E.E.*, 1935, **77**, p. 702.
(*b*) H. A. THOMAS: *ibid.*, 1936, **79**, p. 297.
(*c*) W. JACKSON: *ibid.*, 1936, **79**, p. 573.
(*d*) J. F. GILLIES: *ibid.*, 1940, **86**, p. 69.
(3) (*a*) L. ROHDE and H. SCHWARZ: *Elektrotechnische Zeitschrift*, 1933, **24**, p. 580.
(*b*) L. HARTSHORN and W. H. WARD: *Journal I.E.E.*, 1936, **79**, p. 595.
(4) (*a*) G. G. SMAIL, R. J. BROOKSBANK and W. M. THORNTON: *ibid.*, 1931, **69**, p. 427.
(*b*) F. JOHNSON: *Philosophical Magazine*, 1934, **18**, p. 63.
(5) (*a*) H. SCHWARTZ: *Elektrotechnische Zeitschrift*, 1936, **57**, p. 7.
(*b*) L. ROHDE: *Archiv für Technisches Messen*, May, 1935, p. 59.
(6) F. C. FRANK: *Transactions of the Faraday Society*, 1937, **33**, p. 515.

INSTITUTION NOTES

BRITISH STANDARDS

The Secretary has been asked by the British Standards Institution to draw attention to the following new and revised Specifications:—

Flame-proof Electric Lighting Fittings (B.S. 889).

This specification covers well glass fittings and bulk-head fittings intended for use where the following inflammable gases or vapours may occur in explosive mixture with air:—

Group I. Methane.
Group II. Petroleum vapour. Acetone vapour.
Group III. Town's gas or coke-oven gas containing not more than 60 % hydrogen.

Portable headlamps connected to the circuit by flexible cord are not provided for in this specification. Such lamps are not at present accepted for certification by the Testing Authority.

The dimensions are very carefully specified, and durability, hydraulic, impact and thermal shock, and temperature-rise tests are provided for. The flame-proofness has to be in accordance with B.S. 229.

Copies of this specification can be obtained from the British Standards Institution, 28 Victoria Street, London, S.W.1, price 2s. 3d. post free.

Bolted Flame-proof Cable-Couplers (B.S. 912).

This specification forms one of a series of specifications for electrical apparatus for use in mines, the cable-couplers having also properties capable of being used as detachable dividing boxes. They are so designed as to enable two or more cables of various descriptions to be coupled together, or to enable a cable to be coupled to apparatus. Two types of couplers are covered, i.e. the link type and the contact-pin and contact-tube. In either type it is intended that the two or more units which comprise a coupler shall be attached to one another by bolts, studs or screws, and so constructed as to permit subsequent detachment of the units without disturbing the attachment of the cable thereto.

The specification covers construction, mechanical strength, flame-proof enclosure, insulation, case, self-alignment, contact-pins, contact-tubes and links, and it also gives tables of electrical clearances and standard voltage and current ratings. High-voltage tests are also included.

Copies of the specification can be obtained from the B.S.I., price 2s. 3d. post free.

Motor Starters and Controllers. (B.S. 587).

A reprint of this specification having become necessary, the opportunity has been taken to introduce a few additional clauses, and the specification has therefore been re-issued as the 1940 edition.

The most important additions are the mechanical endurance test and an Appendix on clearances and creepages for motor control gear. A new definition has also been included, this relating to a " damp and dust protecting model."

The Appendix in the 1938 edition dealing with terminal markings is now superseded by B.S. 822, and the Appendix is therefore replaced in the new edition by a cross-reference to that specification.

Copies of the revised specification can be obtained from the B.S.I., price 2s. 3d., post free.

Standard Methods for Testing Rubber (B.S. 902 and 903).

The tests so far standardized by the British Standards Institution have been published in two British Standards as follows:—

B.S. 902. Methods of Testing Latex, Raw Rubber and Unvulcanized Compounded Rubber.

B.S. 903. Methods of Testing Vulcanized Rubber.

These Methods have been based on those of the London advisory Committee for Rubber Research (Ceylon and Malaya) and those of the Research Association of British Rubber Manufacturers as published in "Rubber, Physical and Chemical Properties."

The Methods are applicable to:—

(i) Latex, in a natural or prepared form.
(ii) Raw rubber, in the crude form obtained on the coagulation of latex.
(iii) Unvulcanized compounded rubber obtained from raw rubber by the incorporation of various ingredients.
(iv) Vulcanized rubber, that is to say the product obtained from natural raw rubber by heating it with sulphur and/or sulphur-containing compounds. This latter product may be of a soft extensible character or it may be of a hard inextensible character such as ebonite.

Copies of these British Standards can be obtained from the B.S.I. at the following prices:—B.S. 902, 3s. 9d. post free; B.S. 903, 5s. 4d. post free.

E.R.A. REPORTS

The Secretary has been asked by the British Electrical and Allied Industries Research Association to draw attention to the following Reports which have recently been issued:—

E.R.A. Report Ref. L/T102: High-Voltage Service Testing, with particular reference to the Use of Direct Current. (By A. E. W. Austen, A. Morris Thomas and S. Whitehead.)

This critical review of principles and present-day practice is a first step towards the further development of high-voltage d.c. testing and the extension of its application to station equipment other than cables. The work, of which this review forms a part, is being carried out for the Electricity Commissioners.

Following a general section, the Report deals with the various mechanisms of insulation failure and the types of failure that have been experienced in service.

Standard high-voltage tests are then subjected to more critical examination, with due regard to their efficiency in revealing incipient breakdown without introducing new hazards due to the test itself.

The state of the art of d.c. service testing is fully treated in the major section of the Report, which covers conditions of test, equipment, the control and measurement of voltage, procedure, observations made, and the interpretation of results. This section also contains a summary of the faults found in practice.

Recent developments in service testing are then treated under the following heads:—discharge and ionization detectors; oscillographic tests; dielectric loss measurements.

The Report concludes with a general discussion upon existing methods and possible further developments.

Copies may be obtained from the Association, 15 Savoy Street, London, W.C.2, price 6s. (postage 6d.).

E.R.A. Report Ref. L/T114: The Electric Strength of Solid Dielectrics in Relation to the Theory of Electronic Breakdown. (By A. E. W. Austen and S. Whitehead.)

Methods are described by which the "intrinsic" electric strength of solid dielectrics may be defined and evaluated. It is shown that the magnitudes of, and the effect of temperature and thickness upon, the electric strengths of certain crystals agree with Fröhlich's theory of electronic breakdown, as does also the effect of disordered structure and microstructure in similar instances. On the other hand departures from theory occur with complex organic dielectrics, and also with crystals when certain limits, e.g. of temperature, are exceeded. Some observations are made on the effect of temperature and electric stress upon the conductivity.

Copies may be obtained from the Association, price 3s. (postage 3d.).

A modified version of the Report was published in August, 1940, in the *Proceedings of the Royal Society*, Ser. A, **176**, p. 33.

E.R.A. Report Ref. Z/T52: Methods of Measuring Warmth in Experiments on Space Heating. (Critical Résumé by D. V. Onslow.)

In addition to describing the various methods of measuring warmth, this Report, which is a critical résumé of published information, discusses the requirements for satisfactory heating and cooling. The measurement and effect of air temperature, air velocity and movement, rate of air change, cooling power, radiation and humidity are fully dealt with, details being given of the various measuring instruments and temperature scales which should be employed. Indications are given of the ranges and combinations of conditions within which comfort may be found.

A large number of references have been consulted in the preparation of this Report and are listed in a bibliography at the end.

Copies may be obtained from the Association, price 5s. (postage 2d.).

TRANSFERS

The following transfers were effected by the Council at their meeting held on the 24th October, 1940:—

Student to Graduate

Abercrombie, Thomas William.
Aikman, James, B.Sc.
Aldridge, Leslie James.
Allan, Alexander William, B.Sc.
Allen, Frank, B.Sc.
Arnold, George Frederick.
Atkinson, Alan.
Barclay, Robert Stuart, B.Sc.
Bates, Eric.
Beckett, John Douglas H., B.Sc.
Bell, James Edward.
Bell, Lindsay Gordon, B.E.
Bennett, Frederick James.
Bentall, Anthony Alfred, B.Sc.
Berwin, Charles Arthur.
Betts, Peter.
Biggar, Henry Peter H.
Bowron, Walter Du Cane, B.Sc.(Eng.)
Brassington, Arthur Gerald.
Brooks, George Roderick, B.Sc.
Burns, Rex.

Student to Graduate—continued.

Buxton, Dudley Hayward P.
Bysouth, Kenneth William.
Castle, Charles Alfred.
Chambers, Joseph Arthur.
Chappell, Raymond George.
Chipperfield, Victor James, B.Sc.(Eng.).
Clotworthy, Neil Desmond.
Colgan, Anthony Joseph.
Cook, Stanley Halliday, B.Eng.
Cooper, Richard Anthony, B.Sc.(Eng.).
Cottrell, Seymour.
Court, Gwyn William G., B.Sc.
Dalby, Ernest Kershaw.
Davies, Roy Travers.
Derham, Thomas Reginald K.
Dixon, John George.
Doherty, Stephen Norman, B.Sc.(Eng.).
Dowell, Allan Ure.
Drake, Philip John.
Dunnill, Alan.
Else, William Alan.
Endersby, Francis George.
Farr, Robert Anthony L.
Farrell, Frank Kenneth.
Felgate, Peter Edward.
Field, Peter.
Field, Walter Francis.
Firth, John Alfred P.
Flashman, John Sydney, B.Sc.
Fletcher, Douglas.
Foyer, John.
Francis, Edwin John H.
Frankland, George Douglas.
Gee, Peter Arthur.
Good, Arthur Joseph, B.Sc. (Eng.).
Gregory, Michael Craven.
Groom, Alan Robert.
Gutteridge, James Limbird.
Halbe, Dhundiraj Narayan.
Harper, Bernarr Charles.
Hart, George Valentine.
Hartley, Kenneth Alison, B.Sc.Tech.
Haynes, Joseph.
Higson, Hugh Ward.
Howard, Dennis Robert.
Howard, Richard.
Hunt, Albert, B.Sc.(Eng.).
Hyamson, Theodore David, B.Sc.(Eng.).
Imison, Kenneth Halton, B.Sc.
Inurrieta, Enrique.
Johnson, Henry Gawin.
Joice, William Arnold.
Jones, Edgar Goldstone.
Joseph, Robert Arthur, B.Sc.
Kaul, Permashwar Nath.
Kay, Robert Lindsay.
Kenworthy, Horace Edward.
Kinloch, Colin David.
Kirkwood, George.
Knowles, Arthur Edward.
Knowles, Royston.
Koram, Edmund Manteaw K., B.Sc.(Eng.).
Kumar, Pratap, B.Sc.
Laice, Arthur Lawrence.
Langhorne, Thomas Blacklock.
Lee, Robert Max.
Lester, Frank Duckworth.
Mackay, Frederick Gordon, B.Sc.(Eng.).
Manley, Richard Tapley, B.Sc.
Medlock, Reginald Stuart.
Membry, Eric John, B.Sc. (Eng.).
Murad, Yuszifali Haji.
Newport, Paul Reading.
Nicholson, George Galloway, B.Eng.
Norman, Arthur Ernest.
Oldham, Hugh William.
Pai, Mangalore Srinivas, B.A., B.Sc.(Eng.).
Parker, John Pyne.
Payne, Harold Edward, B.Sc.
Pilling, Edward.
Pulsford, Henry Eric.
Quayle, Ernest, B.Eng.
Redmayne, William Eric.
Reynolds, Bertram Thomas.
Rickman, Alan Owen.
Roberts, Frederick William, B.Sc.
Roberts, John.
Robertson, Archibald Colin C., B.Sc.
Robinson, Cyril.
Rogers, Michael Yeates.
Romans, Geoffrey Owen.
Rose, John Cyril.
Rosenblum, Benjamin, B.Sc.(Eng.).
Rowe, Lester Frederick.
Saxon, Godfrey.
Schofield, Ernest Frederick.
Souter, Lesley Scott (Miss), B.Sc.

Student to Graduate—continued.

Speke, Kenneth.
Stafford, Herbert William H.
Stewart, Gordon Scott.
Sunderland, John, B.Sc. Tech.
Sutton, Peter.
Talcherkar, Krishna Vinayak, B.Sc.(Eng.).
Tatchell, James Albert, B.Sc.(Eng.).
Tattersall, Harry.
Tricker, Charles Spencer.
Tritton, Harold Percy, B.Sc.(Eng.).
Turner, Ronald James, B.Sc.(Eng.).
Twitchin, Frederick Eric D.
Venkataraman, Mayavaram Krishnaswami R.
Vernon, Thomas Victor, B.Eng.
Weston, Jeffrey Dennis, B.Sc.(Eng.).
Williams, Leonard.
Wilshaw, Arthur Anthony.
Wilson, Alan John, B.A.
Wilson, Godfrey Charles I.
Wilson, John Charles.
Windows, Clifford Edgar.
Wolstenholme, Arthur Scott.
Yodmani, Sombati, B.Sc.

ACCESSIONS TO THE REFERENCE LIBRARY

[Note.—The books cannot be purchased at The Institution: the names of the publishers and the prices are given only for the convenience of members; (*) denotes that the book is also in the Lending Library.]

Albert, A. L., *M.S.* Electrical communication. 2nd ed. 8vo. ix + 534 pp. (New York: John Wiley & Sons, Inc.; London: Chapman and Hall, Ltd., 1940.) 30*s.* (*)

—— Fundamental electronics and vacuum tubes. 8vo. ix + 422 pp. (New York: The Macmillan Co., 1938.) 22*s.* 6*d.* (*)

Association of Supervising Electrical Engineers. The A.S.E.E. guide to the eleventh edition (June 1939) of the I.E.E. Regulations for the electrical equipment of buildings. sm. 8vo. 135pp. (London: The Association of Supervising Electrical Engineers, 1940.) *Paper cover* 1*s.* 3*d.*; *cloth cover* 1*s.* 9*d.*

Barton, A. W., *M.A., Ph.D.* A text book on light. 8vo. x + 426 pp. (London: Longmans, Green and Co., Ltd., 1939.) 8*s.* (*)

Beckett, C. S. Generation and transmission. 8vo. 118 pp. (London: Blackie and Son, Ltd., 1940.) 5*s.* (*)

Engineering degree standard. Contains a chapter on power station lay-out and control.

Belling and Lee, Ltd. The suppression of electrical interference with radio reception. Compiled by Technical Staff of Messrs. Belling and Lee, Ltd. 9th ed. sm. 8vo. 90 pp. (Enfield: Belling and Lee, Ltd., 1939.)

Braddick, H. J. J., *Ph.D.* Cosmic rays and mesotrons. Cambridge Physical Tracts. 8vo. ix + 68 pp. (Cambridge University Press, 1939.) 5*s.*

British Electrical Development Association. Modern factory lighting, including special wartime requirements. 8vo. viii + 139 pp. (London: Issued jointly by the B.E.D.A. and the E.L.M.A. Lighting Service Bureau, 2 Savoy Hill, London, W.C.2, 1940.) 8*s.* 6*d.*

Brown, C. H., *Captain.* Deviation and the deviascope. Including the practice and theory of compass adjustment; also, a note of the gyro-compass. 6th ed. 8vo. xi + 278 pp. + 5 charts. (Glasgow: Brown, Son and Ferguson, Ltd., 1939.) 9*s.* (*)

Cable and Wireless Limited. The cable and wireless communications of the world. Some lectures and

papers on the subject, 1924–1939. 8vo. viii + 282 pp. (London: Cable and Wireless Ltd., 1939.)

CABLE MAKERS ASSOCIATION. Repair and maintenance of trailing cables. sm. 8vo. 39 pp. (London: C.M.A., 1940.) 5*s*.

CANFIELD, D. T. The measurement of alternating-current energy. 8vo. xi + 210 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1940.) 12*s*. (*)

On the induction watt-hour meter and its applications. A companion volume to the author's "Vector Representation for electrical metermen," 1931.

CASIMIR, H. B. G. Magnetism and very low temperatures. Cambridge Physical Tracts. 8vo. ix + 95 pp. (Cambridge: University Press, 1940.) 6*s*.

COATES, W. A., and PEARCE, H., *editors*. The switchgear handbook. vol. 2, Apparatus. [*By various contributors*.] 8vo. xii + 267 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1940.) 21*s*. (*)

COCKING, W. T. Television receiving equipment. 8vo. viii + 298 pp. (London: Iliffe and Sons, Ltd., 1940.) 7*s*. 6*d*. (*)

A semi-popular book on cathode ray television receivers.

CONNOR, L. R., *M.Sc.* Statistics in theory and practice. 3rd ed. 8vo. xiv + 383 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 12*s*. 6*d*. (*)

Contains an appendix on Calculating machines, by L. J. Comrie.

COOKE, C. H. C. Alternating current motors and control gear. sm. 8vo. viii + 88 pp. (London: Crosby Lockwood and Son, Ltd., 1939.) 3*s*. 6*d*. (*)

An outline on the selection of suitable motors, their operating characteristics, pplication and installation.

CROOK, W. E., *F/Lt.* Electricity in aircraft. A practical guide for those studying for the Air Ministry "X" Licence. 8vo. vii + 100 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1940.) 5*s*. (*)

DAWES, C. L. Industrial electricity. pt. 1. 2nd ed. 8vo. xvi + 387 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1939.) 12*s*. 6*d*. (*)

DÉVÉDEC, P. Resistance mécanique des conducteurs aériens. 4to. 61 pp. (Bruxelles: Editions Alliance Graphique, 1939.)

EDDY, M. F., *Lieut. U.S. Navy, Rtd.* Aeronautic radio. A manual for operators, pilots, radio mechanics. 8vo. xv + 502 pp. (New York: The Ronald Press Co., 1939.) 27*s*. (*)

EVE, A. S., *C.B.E., D.Sc., LL.D., F.R.S.* Rutherford. Being the life and letters of the Rt. Hon. Lord Rutherford, O.M. 8vo. xvi + 451 pp. (Cambridge: University Press, 1939.) 21*s*. (*)

FIELDING, T. J. Photo-electric and selenium cells. Their operation, construction and uses. 2nd ed. sm. 8vo. vii + 163 pp. (London: Chapman and Hall, Ltd., 1940.) 7*s*. 6*d*. (*)

A revised edition of a work intended for those whose knowledge of the subject is limited.

FINK, D. G. Principles of television engineering. 8vo. xii + 541 pp. (New York; London: McGraw-Hill Book Co., Inc., 1940.) 27*s*. 6*d*. (*)

FLEMING, J. A., *Washington, D.C.* Terrestrial magnetism and electricity. Edited by J. A. F. [*var. contributors*]. (Physics of the earth, VIII.) la. 8vo. xii + 794 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1939.) 52*s*. 6*d*. (*)

GIBBS, J. W., *Ph.D., LL.D.* Vector analysis. A text-book for the use of students of mathematics and physics. Founded upon the lectures of J. W. Gibbs by E. B. Wilson. 2nd ed. 8vo. xviii + 436 pp. (New Haven: Yale University Press, 1931.) 30*s*.

GREEN, S. L. The theory and use of the complex variable. An introduction. 8vo. viii + 136 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1939.) 10*s*. 6*d*. (*)

HARTSHORNE, D. J. How to install overhead equipment for trolleybuses. 8vo. v + 40 pp. (London: Tramway and Railway World Publishing Co., Ltd., 1939.) 4*s*. 6*d*.

HASLETT, C., *C.B.E.* The electrical handbook for women. Edited for The Electrical Association for Women by C. H. Foreword by Sir J. Snell. 3rd ed. sm. 8vo. 474 pp. (London: The English Universities Press Ltd., 1939.) 5*s*. (*)

—— Household electricity. sm. 8vo. 216 pp. (London: The English Universities Press, Ltd., 1939.) 2*s*. 6*d*.

HERBERT, T. E., and PROCTER, W. S. Telephony. A detailed exposition of the telephone system of the British Post Office. Supplement to volume 2. 8vo. vi + 97 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1940.) 3*s*. 6*d*. (*)

HIRST, A. W., *M.Sc.(Eng.)*. Introduction to electrical machines. 8vo. v + 122 pp. (London: Blackie and Son, Ltd., 1939.) 5*s*. (*)

On fundamental principles and a companion volume to the book by C. S. Beckett, Engineering degree standard.

HISCOX, W. J. Factory lay-out, planning and progress. 2nd ed., revised by J. Stirling. 8vo. viii + 195 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1939.) 7*s*. 6*d*. (*)

HOLMSTROM, J. E., *Ph.D.* Records and research in engineering and industrial science. A guide to the production, extraction, integrating, storekeeping, circulation and translation of technical knowledge. 8vo. xii + 302 pp. (London: Chapman and Hall, Ltd., 1940.) 15*s*.

HOPE-JONES, F. Electrical timekeeping. With a foreword by Dr. H. Spencer Jones. 8vo. xix + 275 pp. (London: N.A.G. Press, Ltd., 1940.) 10*s*. (*)

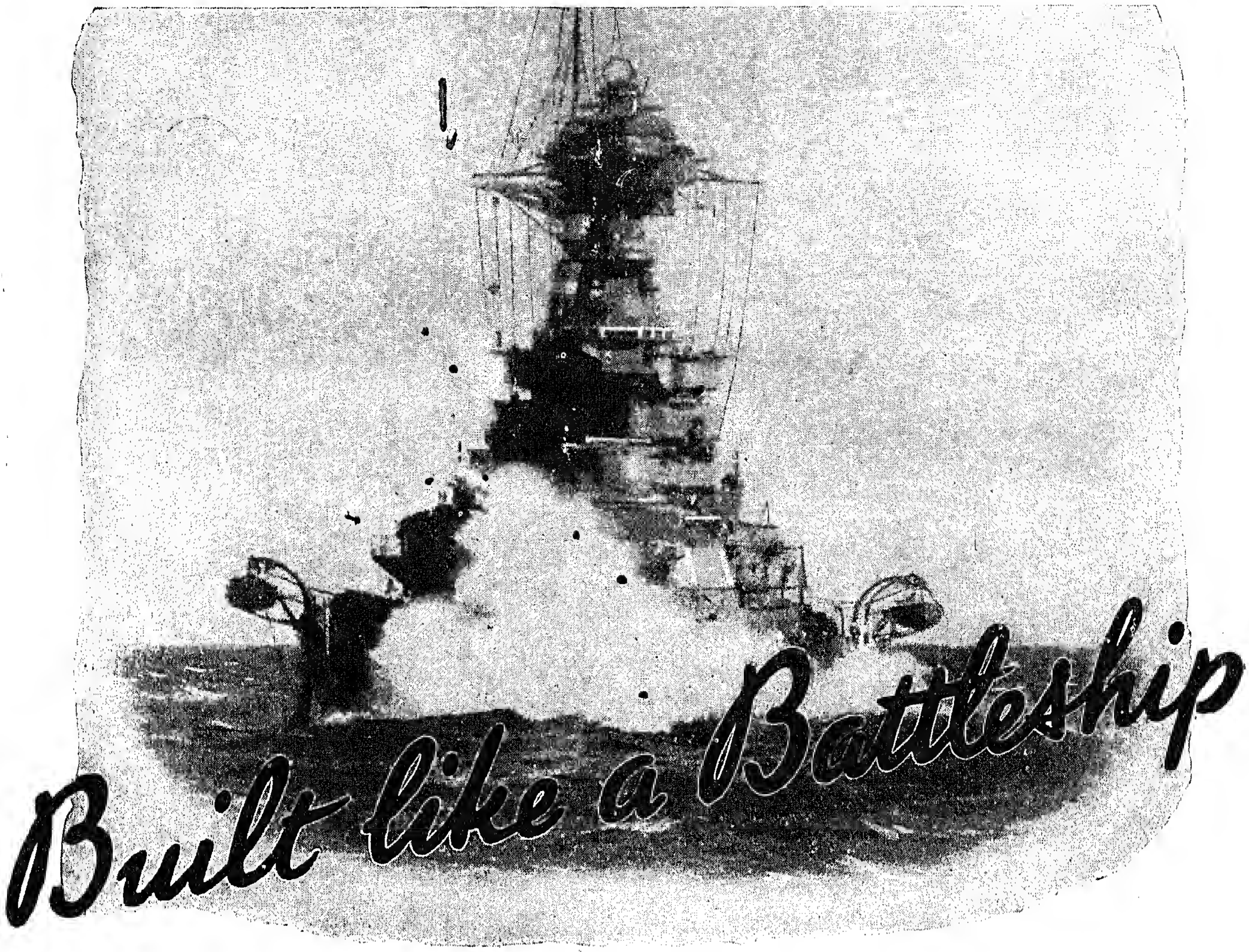
IBBETSON, W. S. Electric wiring theory and practice for wiremen, engineers and students, including special chapters on illumination, motors and generators. 6th ed. sm. 8vo. vii + 264 pp. (London: E. and F. N. Spon, Ltd., 1939.) 6*s*. (*)

INTERNATIONAL CONFERENCE ON LARGE HIGH-TENSION ELECTRIC SYSTEMS, PARIS, 1939. Papers presented for discussion at the 10th session, 1939. 3 vol. 8vo. (Paris; London: C.I.G.R.E., 15 Savoy Street, W.C.2.) 63*s*.

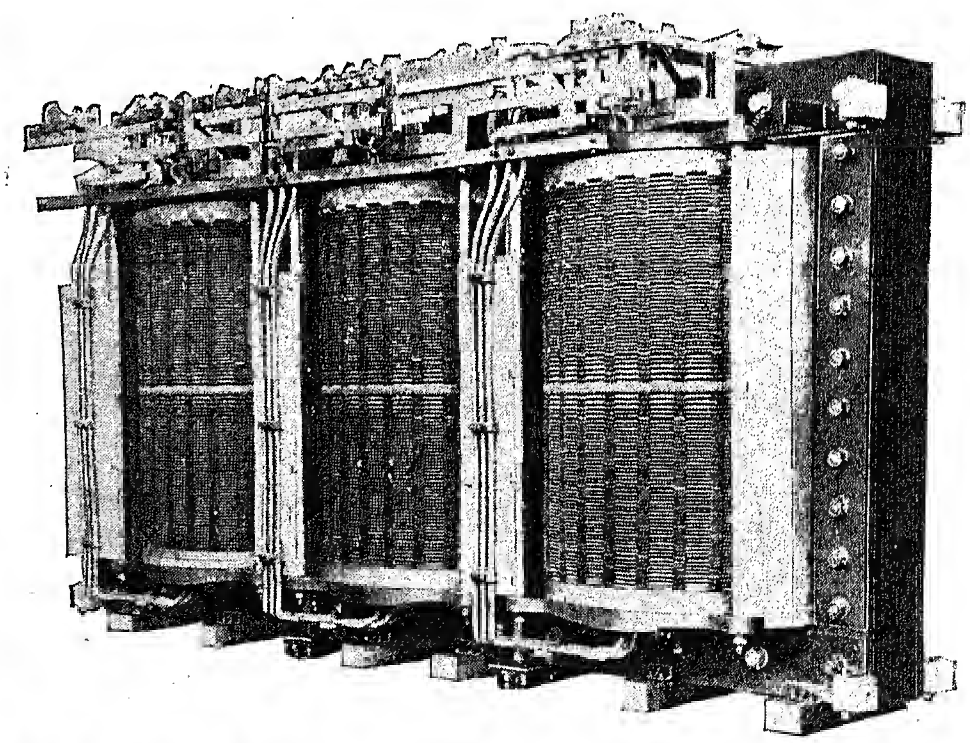
JOHNSON AND PHILLIPS, LTD. The economic and engineering features of electrification in rural areas. 8vo. 76 pp. (London: Johnson and Phillips, Ltd., *n.d.*)

KERSHAW, J. W. Elementary internal combustion engines. 2nd ed. sm. 8vo. 211 pp. (London: Longmans, Green and Co., 1931.) 5*s*. (*)

KIESLING, B. C. Talking pictures: how they are made and how to appreciate them. 8vo. xi + 332 pp. (London: E. and F. N. Spon, Ltd., 1939.) 10*s*. (*)



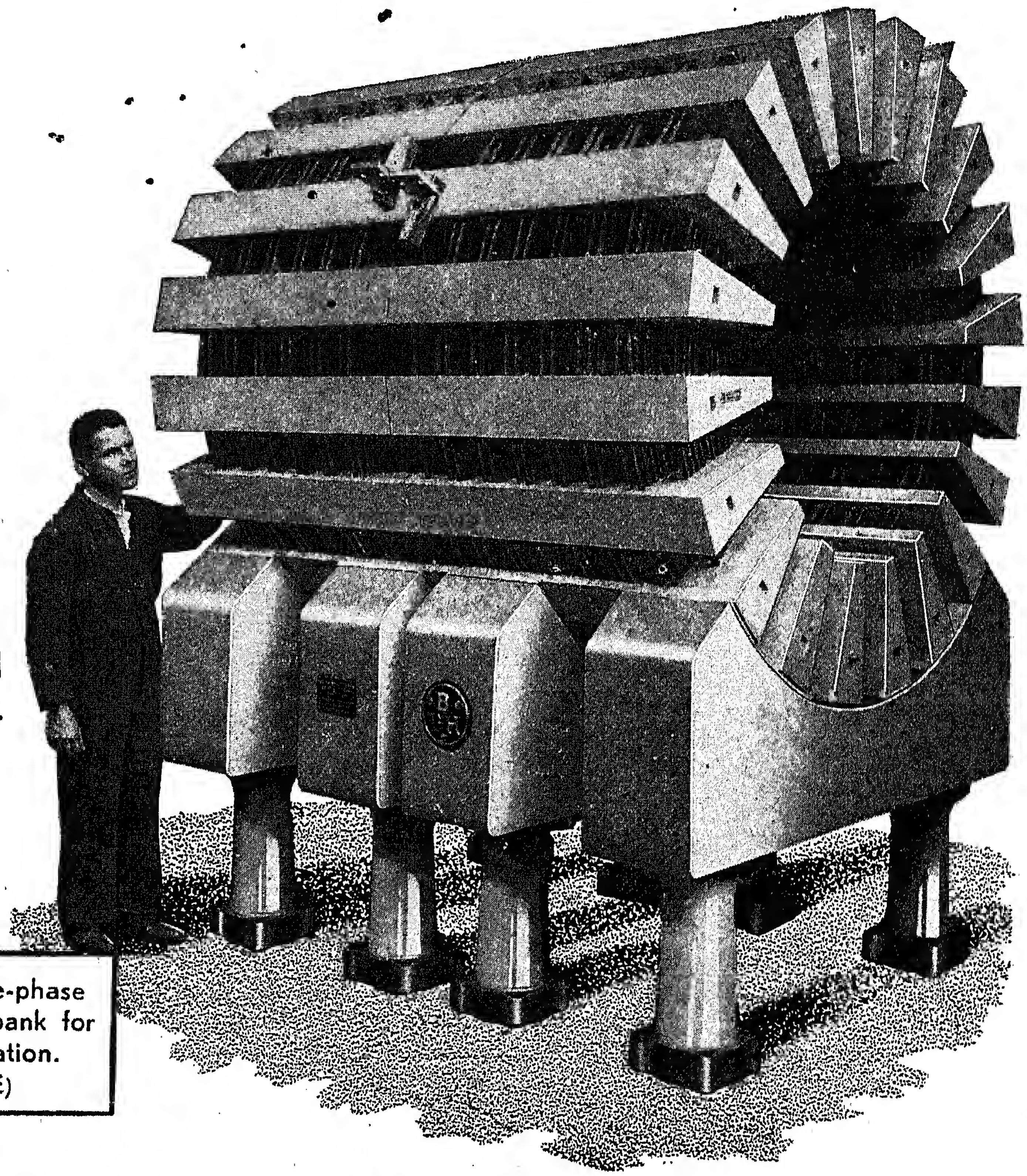
Strength—ability to stand up to abnormal stresses—is as essential to a transformer in its particular field as to a battleship. Here is an outstanding feature of Hackbridge transformers which, while superficially similar to competing makes, have amongst other important features one that is unique—their special unit construction whereby on each limb the primary / secondary winding assembly is individually clamped between robust end rings tied together by steel tie bars affording a construction tremendously strong against short circuits and preventing mutual movement of primary and secondary coils under stress—typical this of the thought and experience characteristic of Hackbridge design.



HACKBRIDGE THE TRANSFORMER *SPECIALISTS*

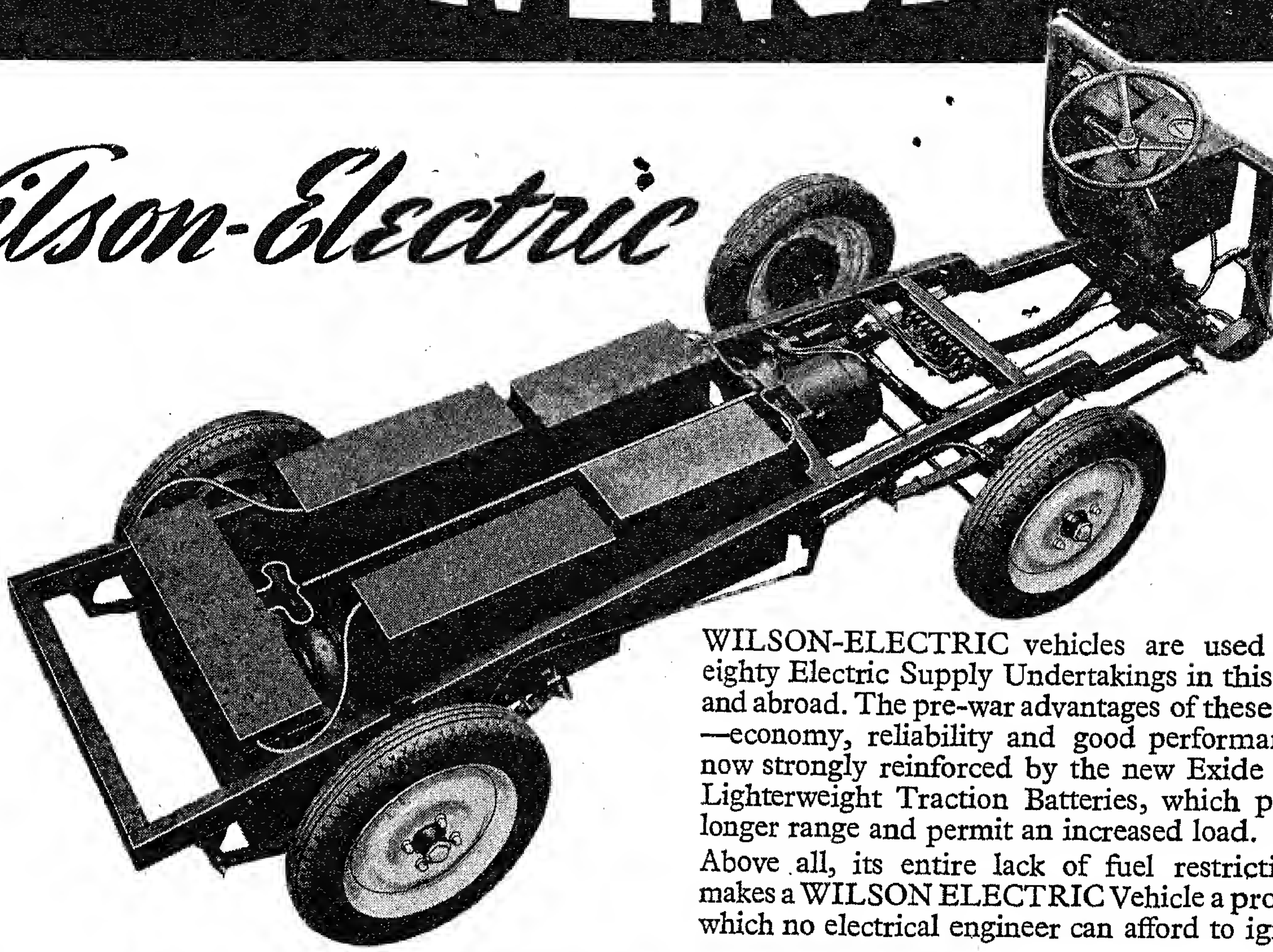
HACKBRIDGE ELECTRIC CONSTRUCTION CO., LTD., WALTON-ON-THAMES, SURREY

MALAY STATES: The Alliance Engineering Co. Ltd., 6 & 7, Telegraph Street, SINGAPORE. Also at Post Box 359, KUALA LUMPUR. **INDIA:** A. C. Bottomley & Co. Ltd., Stronach House, Graham Road, Ballard Estate, BOMBAY. Steam & Mining Equipment (India) Ltd., 7, Church Lane, CALCUTTA. **AUSTRALIA:** Hewittic Electric Co. Ltd., Kembla Buildings, Margaret Street, SYDNEY. **SOUTH AFRICA:** Hubert Davies & Co. Ltd., Hudaco House, Rissik Street, JOHANNESBURG. Also at:—Durban, Cape Town, Port Elizabeth, East London, Salisbury, Bulawayo & N'Dola. **NEW ZEALAND:** The Alliance Electrical Co. Ltd., 41, A.M.P. Buildings, First Floor, Custom House Quay, WELLINGTON. **CANADA:** The Northern Electric Co. Ltd., 1620, Notre Dame St. West, Montreal. QUEBEC. **SOUTH AMERICA:** H. W. Roberts & Co. Ltd., Piedras, 353, BUENOS AIRES. (Agents for Argentine & Uruguay.)



DAVENSET

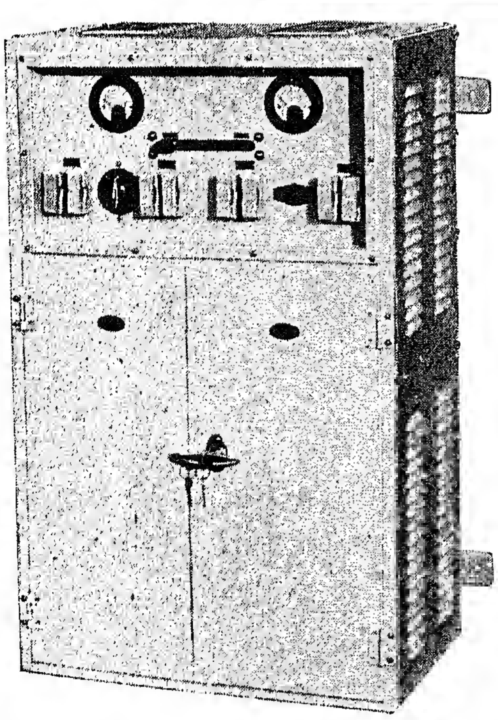
Wilson-Electric



WILSON-ELECTRIC vehicles are used by over eighty Electric Supply Undertakings in this country and abroad. The pre-war advantages of these vehicles —economy, reliability and good performance—are now strongly reinforced by the new Exide Ironclad Lighterweight Traction Batteries, which provide a longer range and permit an increased load.

Above all, its entire lack of fuel restriction now makes a WILSON ELECTRIC Vehicle a proposition which no electrical engineer can afford to ignore.

DAVENSET DRIMET METAL RECTIFIERS



are individually designed and produced to suit all types of requirements. Fourteen years of specialisation in rectifiers and battery charging apparatus enable us to offer equipment in the most practical form, to satisfy the most exacting demands.

DAVENSET AUTOMATIC PUMPS

provide the ideal equipment for cellar-draining and sump-clearing purposes. They are entirely self-contained, the float and switch mechanism being enclosed in the main housing, so that installation is rapid and simple. Complete submersion does not affect their operation. Approved by Home Office for Air Raid Shelter drainage.

Full particulars on application to:

PARTRIDGE WILSON & CO., LTD.

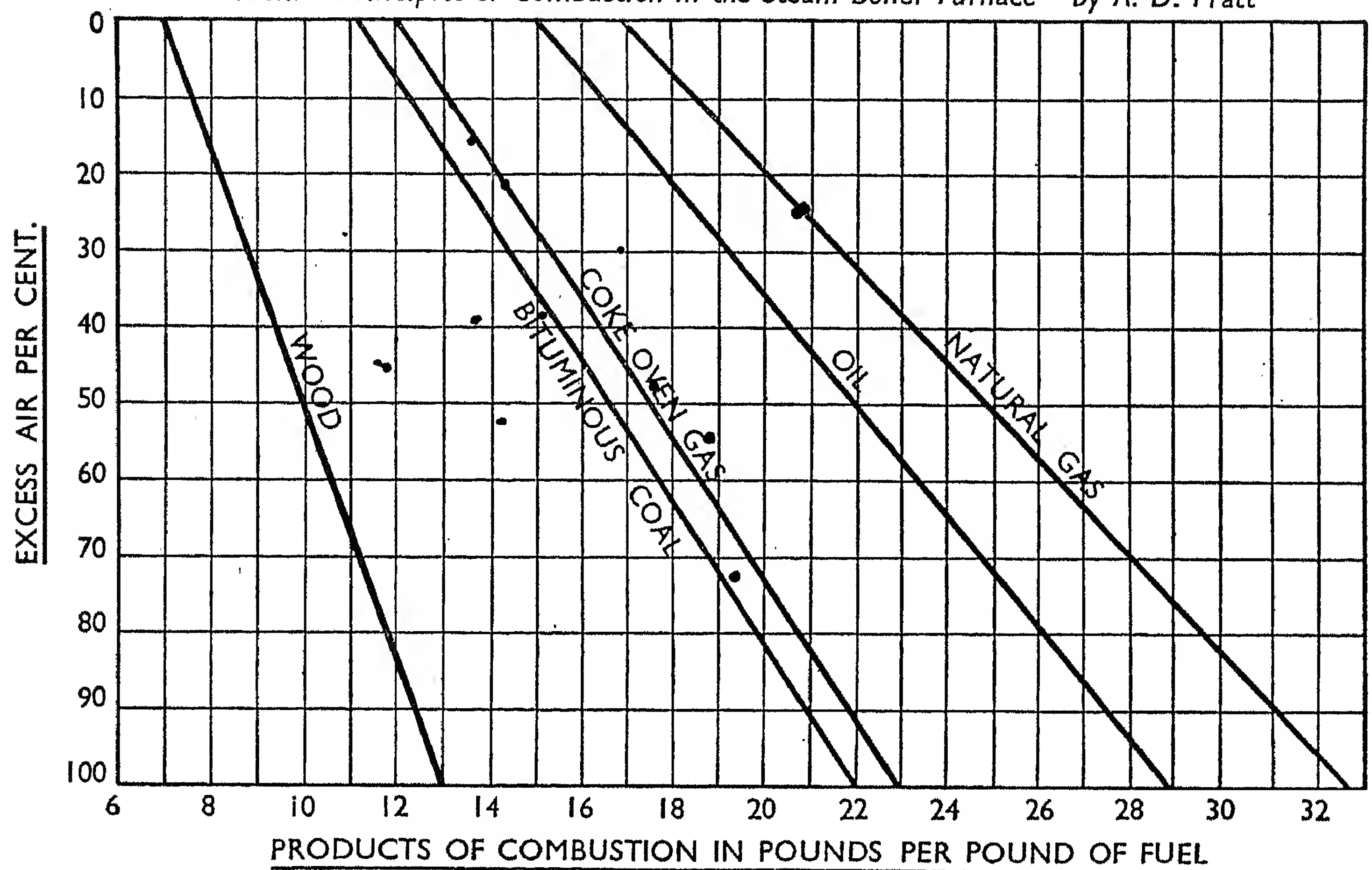
DAVENSET WORKS · LEICESTER


R.N.
A.T.S.
R.N.V.R.
L.D.V.
A.R.P.
R.A.M.C.
A.F.S.
R.N.R.
R.A
R.A.F.
R.E
R.A.S.C.
A.A.
B.I.

What does CO_2 mean?

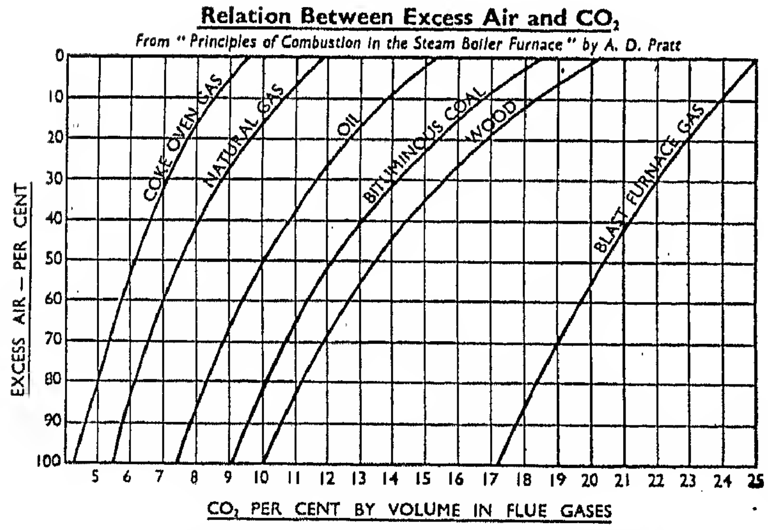
Relation Between Excess Air and Products of Combustion

From "Principles of Combustion in the Steam Boiler Furnace" by A. D. Pratt



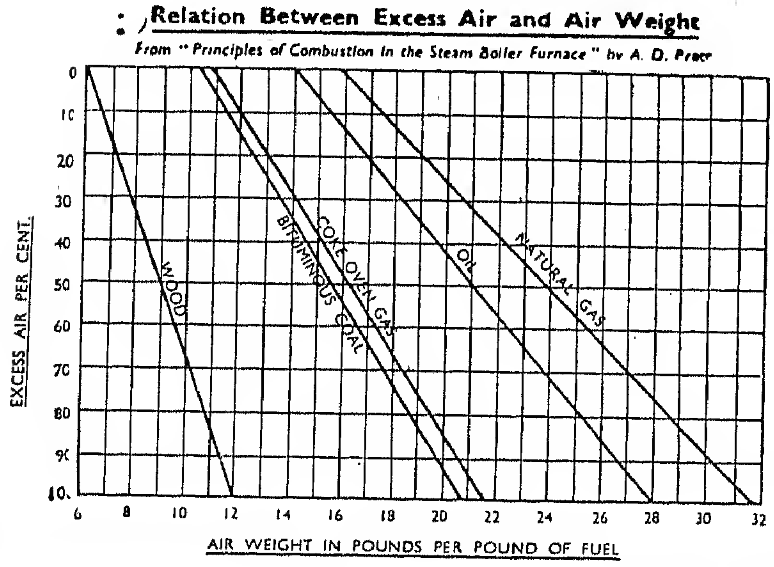
Relation Between Excess Air and CO_2

From "Principles of Combustion in the Steam Boiler Furnace" by A. D. Pratt



Relation Between Excess Air and Air Weight

From "Principles of Combustion in the Steam Boiler Furnace" by A. D. Pratt



FROM the above chart it will be seen that when burning 1 lb. of coal, an increase from 20% to 100% excess air means that the weight of the products of combustion is increased by approximately 8½ lb.

Our previous advertisement showed that this increase in excess air involved an increase in the weight of air for combustion by the same amount. Thus the forced draught and the induced draught fans together must handle approximately 17 lb. more air and products of combustion than that necessary for efficient combustion.

In the case of a boiler for 175,000 lb. of steam per hour, with 20% excess air the fan motors would be rated at 196 h.p., which would be increased at 100% excess air to 875 h.p., thus involving an increase in electrical input to the motor terminals of 570 KW. Assuming 20 hours per day and 300 days per year, at ½d. per KWH this unnecessary expenditure in fan power amounts to £7,130 per annum, which in itself is more than sufficient to pay for a Bailey furnace. This sum capitalised at 4% interest for 20 years amounts to over £212,000. Bailey furnace construction permits operation with minimum excess air over a very wide range of load, so that the saving in fan power debit alone gives a very handsome return on capital invested.

Criticism might be made that the limits are too wide in the foregoing example, but even if operation is assumed with 60% excess air, then the unnecessary fan power expenditure is £2,840 per annum, which when capitalised amounts to £84,570. However, when it is realised that this fan power debit is one of the smallest items entering into the balance sheet, it will be obvious that Bailey furnace construction is in the last analysis the cheapest construction which can be installed.

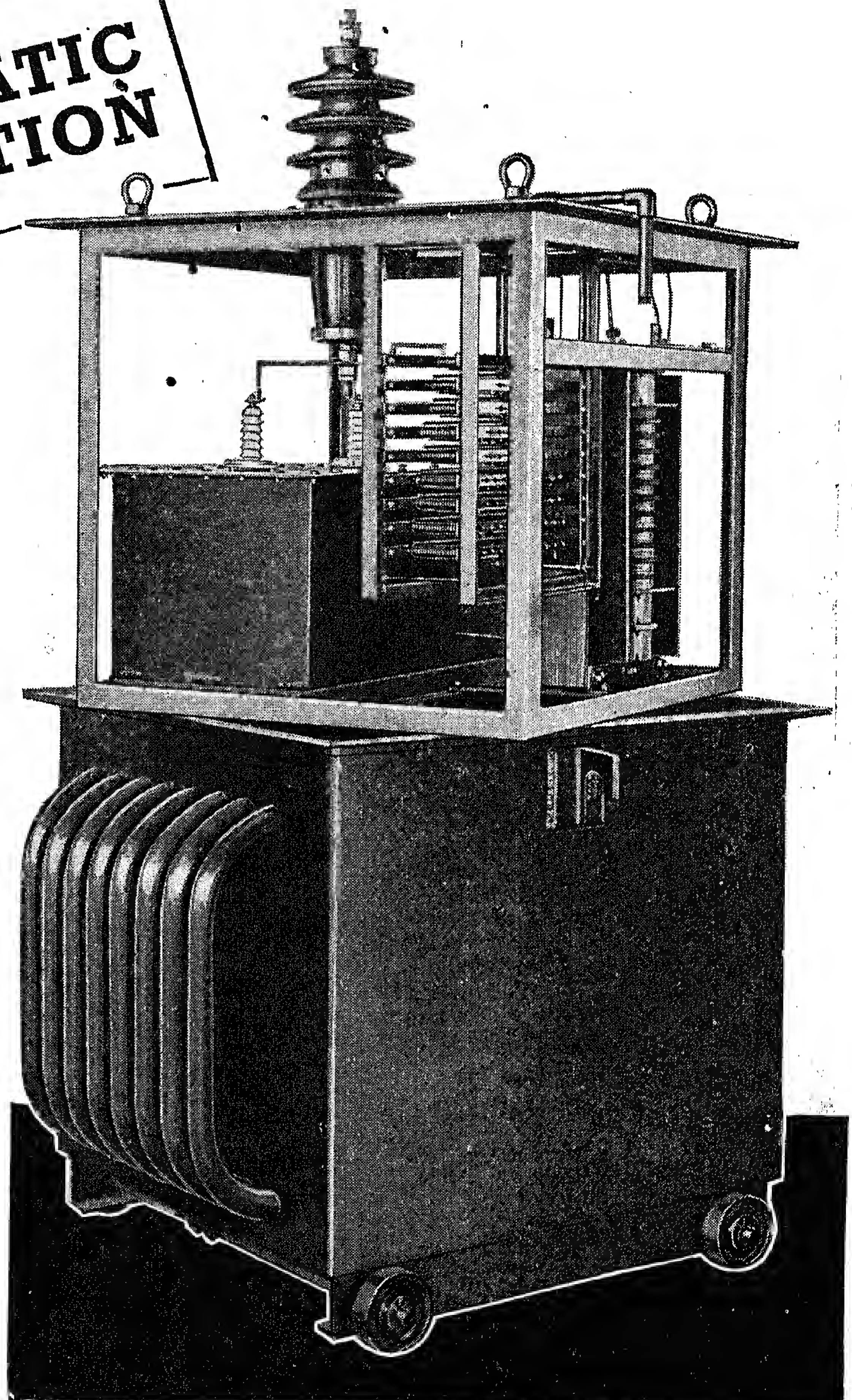
(For convenience we reproduce the charts from our Nos. 1 and 2 advertisements in this series, showing the relationship between excess air and CO_2 and weight of air for combustion.)

This is the third of a series of three advertisements

BABCOCK & WILCOX LTD. BABCOCK HOUSE, FARRINGDON ST. LONDON, E.C.4.

SELENIUM RECTIFIERS IN SERVICE No. 3

ELECTROSTATIC PRECIPITATION



OWING to its relatively small size and weight the *Standard* Selenium Rectifier is particularly suitable for high tension application. The illustration shows an oil-immersed rectifier with the unit withdrawn from the tank. It includes a high-tension transformer, rectifier and condensers and has a continuous output of 40 kilovolts at a current of 50 milliamps. The overall dimensions are 42 inches by 48 inches by 52 inches high.

The unit was supplied to the Whessoe Foundry & Engineering Co., Ltd., for electrostatic precipitation of tarfog from gas.

Full details will gladly be supplied upon request.

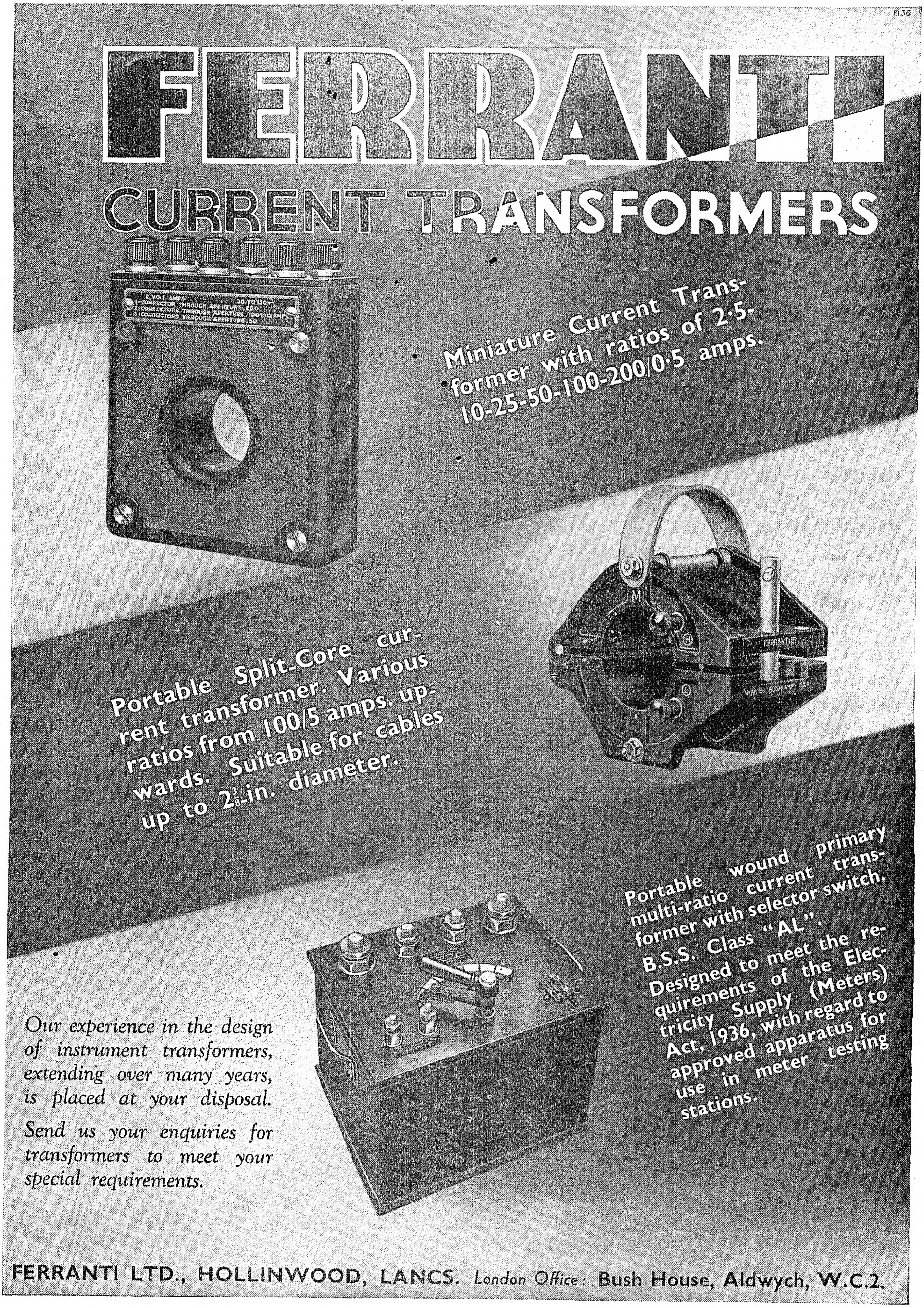
Standard Telephones and Cables Limited

OAKLEIGH ROAD, NEW SOUTHGATE, LONDON, N.11

Telephone: ENTerprise 1234

LIST OF ADVERTISERS IN THIS ISSUE

	PAGE
Automatic Coil Winder & Electrical Equipment Co., Ltd.	xii
Babcock & Wilcox, Ltd.	viii
British Insulated Cables, Ltd.	vii
British Thomson-Houston Co., Ltd.	iv
Cable Makers' Association	i
Ferranti, Ltd.	xiv
General Electric Co., Ltd.	x
Hackbridge Electric Construction Co., Ltd.	ii
Keith Blackman, Ltd.	xiii
Liverpool Electric Cable Co., Ltd.	xiii
London Electric Wire Co. & Smiths, Ltd.	xiii
Muirhead & Co., Ltd.	iii
Partridge Wilson & Co., Ltd.	v
Siemens Bros. & Co., Ltd.	vi
Smith (Frederick) & Co.	xiii
Standard Telephones & Cables, Ltd.	ix
Westinghouse Brake & Signal Co., Ltd.	xi
Zenith Electric Co., Ltd.	xii


FERRANTI
CURRENT TRANSFORMERS
Miniature Current Transformer with ratios of 2·5-10-25-50-100-200/0·5 amps.
Portable Split-Core current transformer. Various ratios from 100/5 amps. upwards. Suitable for cables up to 2⅜-in. diameter.
Portable wound primary multi-ratio current transformer with selector switch, B.S.S. Class "AL". Designed to meet the requirements of the Electricity Supply (Meters) Act, 1936, with regard to approved apparatus for use in meter testing stations.
Our experience in the design of instrument transformers, extending over many years, is placed at your disposal.
Send us your enquiries for transformers to meet your special requirements.
FERRANTI LTD., HOLLINWOOD, LANCS. London Office: Bush House, Aldwych, W.C.2.

NORTH-WESTERN CENTRE.

Chairman.—B. A. G. CHURCHER, M.Sc.
Hon. Secretary.—L. H. A. CARR, M.Sc.Tech., "Oakleigh," Cambridge Road, Hale, Altrincham, Cheshire.

SCOTTISH CENTRE.

Chairman.—PROF. S. PARKER SMITH, D.Sc.
Hon. Secretary.—R. B. MITCHELL, 154, West George Street, Glasgow, C.2.
Hon. Asst. Secretary.—H. V. HENNIKER, 172, Craigleith Road, Edinburgh.

Dundee Sub-Centre.

Chairman.—A. A. B. MARTIN, B.Sc.
Hon. Secretary.—P. PHILIP, c/o Electricity Supply Dept., Dudhope Crescent Road, Dundee.

SOUTH MIDLAND CENTRE.

Chairman.—H. JOSEPH.
Acting Hon. Secretary.—R. H. RAWLL, 125, Wentworth Road, Harbourne, Birmingham, 17.

East Midland Sub-Centre.

Chairman.—B. C. BAYLEY, M.B.E.
Hon. Secretary.—J. F. DRIVER, Brighton House, Herrick Road, Loughborough.

WESTERN CENTRE.

Chairman.—H. R. BEASANT.
Hon. Secretary.—G. L. COVENTON, "Wyndcliff," Oxstalls Lane, Gloucester.

Devon and Cornwall Sub-Centre.

Chairman.—E. F. KILL.
Acting Hon. Secretary.—C. J. HOCKING, Plymouth Corporation Electricity Dept., Armada Street, Plymouth.

West Wales (Swansea) Sub-Centre.

Chairman.—T. H. DAVIES.
Hon. Secretary.—J. E. DAWTRY, c/o British Electrical Repairs, Ltd., Neath Road, Hafod, Swansea.

Hampshire Sub-Centre (directly under the Council).

Chairman.—COMDR. H. H. ROGERS, R.N.
Hon. Secretary.—A. G. HISCOCK, c/o City of Portsmouth Electricity Undertaking, 111, High Street, Portsmouth, Hants.

Northern Ireland Sub-Centre (directly under the Council).

Chairman.—F. W. PARKINSON.
Hon. Secretary.—C. M. STOUPE, B.Sc., 32, Kansas Avenue, Antrim Road, Belfast.

INFORMAL MEETINGS.

Chairman of Committee.—

METER AND INSTRUMENT SECTION.

Chairman.—C. W. MARSHALL, B.Sc.

TRANSMISSION SECTION.

Chairman.—H. J. ALLCOCK, M.Sc.

WIRELESS SECTION.

Chairman.—W. J. PICKEN.

OVERSEAS COMMITTEES.

AUSTRALIA.

New South Wales.

Chairman.—R. V. HALL, B.E.
Hon. Secretary.—C. A. SAXBY, Electrical Engineering Branch, Dept. of Public Works, Bridge Street, Sydney.

Queensland.

Chairman and Hon. Secretary.—J. S. JUST, c/o Box 1067N, G.P.O., Brisbane.

South Australia.

Chairman and Hon. Secretary.—F. W. H. WHEADON, Kelvin Building, North Terrace, Adelaide.

Victoria and Tasmania.

Chairman and Hon. Secretary.—H. R. HARPER, 22-32, William Street, Melbourne.

Western Australia.

Chairman.—J. R. W. GARDAM.
Hon. Secretary.—A. E. LAMBERT, B.E., c/o City of Perth Electricity and Gas Dept., 132, Murray Street, Perth.

CEYLON.

Chairman.—MAJOR C. H. BRAZEL, M.C.
Hon. Secretary.—D. P. BENNETT, c/o Messrs. Walker, Sons & Co., Ltd., Colombo.

INDIA.

Bombay.

Chairman.—R. G. HIGHAM.
Hon. Secretary.—A. L. GUILFORD, B.Sc.Tech., Electric House, Post Fort, Bombay.

Calcutta.

Chairman.—S. W. REDCLIFT.
Hon. Secretary.—D. H. P. HENDERSON, c/o Calcutta Electric Supply Corporation, Post Box 304, Calcutta.

Lahore.

Chairman.—V. F. CRITCHLEY.
Hon. Secretary.—SAUDAGAR SINGH, M.Sc., Electrical Engineer to Government, Punjab, McLeod Road, Lahore.

Madras.

Chairman.—MAJOR E. G. BOWERS, M.C.
Hon. Secretary.—W. LEC. DE BRUYN, District Electrical Engineer, M. & S.M. Railway, Perambur, Madras.

NEW ZEALAND.

Chairman.—F. T. M. KISSEL, B.Sc.
Hon. Secretary.—M. A. PIKE, P.O. Box 749, Wellington.

SOUTH AFRICA

Transvaal.

Chairman and Hon. Secretary.—W. ELSDON-DEW, Box 4563, Johannesburg.

LOCAL HONORARY SECRETARIES ABROAD.

ARGENTINA: R. G. PARROTT, Tucuman 117, Buenos Aires.
CANADA: A. B. COOPER, Ferranti Electric Ltd., Mount Dennis, Toronto, 9.
CAPE, NATAL, AND RHODESIA: G. H. SWINGLER, City Electrical Engineer, Corporation Electricity Dept., Cape Town.
FRANCE: P. M. J. AILLERET, 20, Rue Hamelin, Paris (16e).
HOLLAND: W. LULOFS, D.Ing., Tesselschadestraat, 1, Amsterdam-West.
INDIA: S. W. REDCLIFT, Electrical Adviser and Electrical Inspector to Government of Bengal, 1, Harish Mukherji Road, Elgin Road P.O., Calcutta.
JAPAN: I. NAKAHARA, No. 40, Ichigaya Tanimachi, Ushigomeku, Tokio.
NEW SOUTH WALES: V. J. F. BRAIN, B.E., Chief Electrical Engineer, Department of Public Works, Bridge Street, Sydney.
NEW ZEALAND: M. A. PIKE, P.O. Box 749, Wellington.
QUEENSLAND: J. S. JUST, c/o Box 1067N, G.P.O., Brisbane.
SOUTH AUSTRALIA: F. W. H. WHEADON, Kelvin Building, North Terrace, Adelaide.
TRANSVAAL: W. ELSDON-DEW, Box 4563, Johannesburg.
UNITED STATES OF AMERICA: GANO DUNN, c/o The J. G. White Engineering Corporation, 80, Broad Street, New York, N.Y.
VICTORIA AND TASMANIA: H. R. HARPER, 22-32, William Street, Melbourne.
WESTERN AUSTRALIA: PROF. P. H. FRAENKEL, B.E., The University of Western Australia, Crawley, Perth.

STUDENTS' SECTIONS.

LONDON.

Chairman.—B. Drake, B.Sc.(Eng.).
Hon. Secretary.—M. F. Burrage, 6, Glenwood Gardens, Ilford, Essex.

NORTH-WESTERN.

Chairman.—E. G. Jones, B.A.
Hon. Secretary.—C. B. Simpson, B.Sc.Tech., Switchgear Engineering Dept., Metropolitan-Vickers Electrical Co., Ltd., Trafford Park, Manchester, 17.

SCOTTISH.

Chairman.—W. S. H. Maclachlan.
Hon. Secretary.—W. Paterson, The Royal Technical College, Glasgow, C.1.

NORTH-EASTERN.

Chairman.—R. Bruce, M.Sc.
Hon. Secretary.—D. H. Towns, B.Sc., 66, Mountfield Gardens, Newcastle-on-Tyne, 3.

MERSEY AND NORTH WALES (LIVERPOOL).

Chairman.—F. B. Atkinson, B.Eng.
Hon. Secretary.—G. S. Stewart, Laboratories of Applied Electricity, The University, Liverpool, 3.

SOUTH MIDLAND.

Chairman.—D. H. Ray.
Hon. Secretary.—C. H. Bottrell, 51, York Road, Edgbaston, Birmingham, 16.

NORTH MIDLAND.

Chairman.—S. R. Brown.
Hon. Secretary.—A. E. Cunningham, "Wyndley," Ings Avenue, Guiseley, Leeds.

SHEFFIELD.

Chairman.—C. C. Hall.
Hon. Secretary.—J. H. H. Teece, B.Sc.(Eng.), c/o Metropolitan-Vickers Electrical Co., Ltd., Howard Gallery, Chapel Walk, Sheffield, 1.

BRISTOL.

Chairman.—
Hon. Secretary.—J. W. Dorrinton, 45, Trelawney Road, Cotham, Bristol, 6.

THE I.E.E. BENEVOLENT FUND.

There are many members and former members of The Institution who are finding life difficult. Please help them by sending an annual subscription or a donation to the I.E.E. Benevolent Fund.

The object of the Fund is: "To afford assistance to necessitous members and former members (of any class) of The Institution of Electrical Engineers who have paid their subscription for at least five years consecutively or compounded therefor, and to the dependents of such members or former members."

Subscriptions and Donations should be addressed to

THE HONORARY SECRETARY, THE BENEVOLENT FUND,
THE INSTITUTION OF ELECTRICAL ENGINEERS,
SAVOY PLACE, W.C.2.

LOCAL HON. TREASURERS OF THE FUND.

Irish Centre: J. A. Butler. *North-Eastern Centre:* V. A. H. Clements. *North Midland Centre:* R. M. Longman. *Sheffield Sub-Centre:* W. E. Burnand. *North-Western Centre:* T. E. Herbert. *Mersey and North Wales (Liverpool) Centre:* A. C. Livesey. *Scottish Centre: (Glasgow)* A. Lindsay; *(Edinburgh)* D. S. Munro. *Dundee Sub-Centre:* P. Philip. *South Midland Centre:* H. Hooper. *Western Centre: (Bristol)* E. P. Knill; *(Cardiff)* E. Jones. *Hampshire Sub-Centre:* W. P. Conly, M.Sc.

PRINTED BY UNWIN BROTHERS LIMITED, LONDON AND WOKING